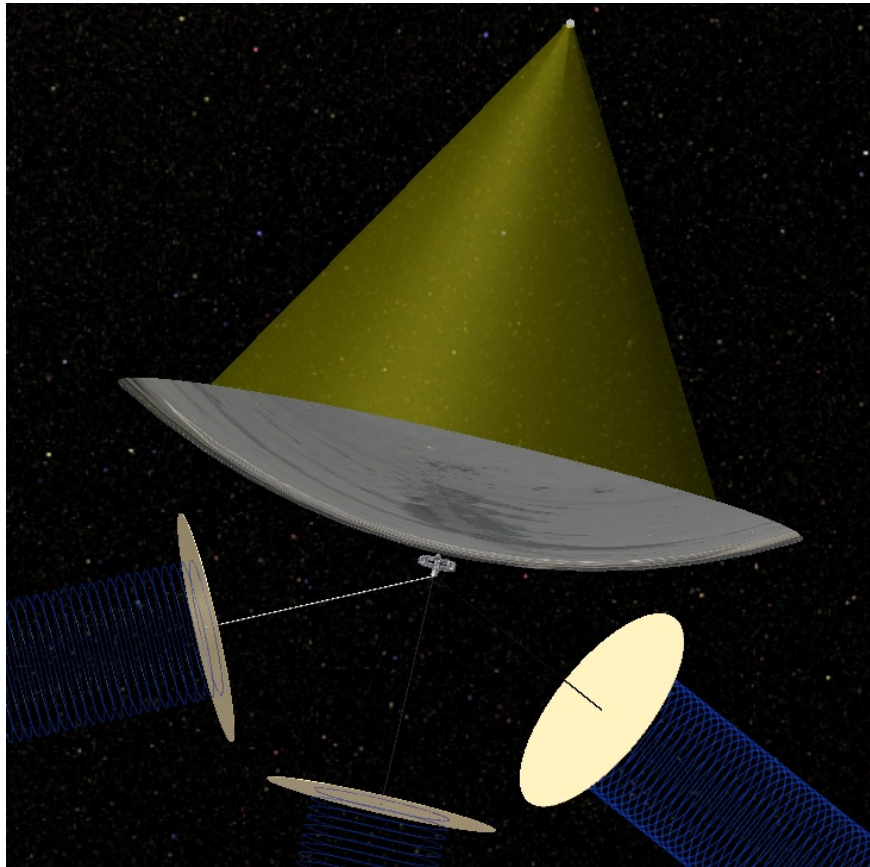


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Brendan Dessanti  
Georgia Institute of Technology  
School of Aerospace Engineering



**The Space Power Grid Approach to Space Solar Power**

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# **The Space Power Grid Approach To Space-Based Solar Power**

**Special Problems Report**

**Brendan Dessanti**

Advisor: Dr. Narayanan Komerath  
Experimental Aerodynamics and Concepts Group  
Daniel Guggenheim School of Aerospace Engineering  
Georgia Institute of Technology  
Atlanta GA 30332-0150

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# Chapter 1

## Introduction

### 1.1 Space-Based Solar Power Background

The idea of using wireless power transmission to create a large system of delivering electrical power throughout the world dates back to Nikola Tesla [1]. Tesla demonstrated wireless power transmission over a distance of 30 miles in 1897 [2]. The idea of using space as a means of power relay has been around for several decades. As early as 1945, Arthur C. Clarke pointed out that the unique properties of geostationary earth orbit (GEO) made it a convenient location for a power relay system [3]. Space-based solar power (SSP), the idea of collecting solar power in space and beaming the power to rectennas on the Earth's surface using RF waves, is often credited to Peter Glaser [4] of the Arthur D. Little, Inc. company. Glaser's architecture utilized geosynchronous earth orbit (GEO) for the location of the solar power satellite. His architecture utilized microwave power beaming for transmission and photovoltaic devices for energy conversion.

Since then, space solar power has seen periods of high interest, often coinciding with certain public policy objectives. In the late 1970s, NASA and the DOE studied the feasibility of the space solar power concept [5] [6]. A system such as space solar power requiring a large number of routine launches could help provide justification for developing a reusable space transportation vehicle like the space shuttle. In the 1990s, interest in developing space solar power returned. The NASA "Fresh Look" study [7] [8] evaluated different architecture concepts. This study attempted to assess whether space solar power was now a viable option given improvements in technology and changes in the economic and political environment. The SPS2000 initiative generated significant interest among the International Space Station partners [9] [10] [11] [12].

More recently, there has been significant interest in space solar power over the past decade in the United States [13] [14] and internationally [15] [16]. Rising energy costs and global warming concerns have prompted significant interest in renewable energy alternatives such as space solar power. In Japan, JAXA (Japan Aerospace Exploration Agency) has shown great interest of the space agencies in moving towards space solar power. JAXA has plans for a Low Earth Orbit demonstration of wireless power beaming by 2015 [17] and plans to establish a functioning solar power satellite by 2040. Japan has committed \$21 billion towards the development of a 1GW solar power satellite. China also has plans to complete a space solar power demonstration by 2025 [18]. In recent years, India has also expressed strong interest in non-fossil energy sources including space solar power [19]. India has recognized developing space solar power as a potential strategic partnership with the United States with the NSS-Kalam initiative [20]. In 2012, the

NASA Institute of Advanced Concepts funded a study into a solar power satellite concept proposed by John Mankins [21].

## 1.2 Difficulties in Implementing Space Solar power

### 1.2.1 Key Issues

Reproduced from [22]:

SSP architecture analysis shows an orders of magnitude gap in economic viability, and large geosynchronous orbit based architectures show no evolutionary path towards space solar power. At the root of the problem is the sheer magnitude of establishing a power plant in space. Generating significant quantities of power requires a large amount of mass be launched into orbit. High launch cost rates dictate high system costs for any space based solar power system. The large beaming distance of geosynchronous orbit and low frequency of microwave based systems, coupled with the low efficiency of photovoltaic conversion have made it difficult to present a viable business plan for space solar power. As a result of the orbit location and frequency selection of traditional approaches, the transmitter and receiver sizes are pushed to diameters on the order of kilometers, making it difficult to establish an evolutionary approach to jump-starting SSP. Innovative solutions to the space solar power problem that offer significant improvements in economic viability and that allow for an evolutionary approach are needed in order to generate interest among government and/or private entities.

### 1.2.2 Assessing Viability

Our rule of thumb for viability of SSP developed from architecture studies from our group is the value of the parameter  $k$  which was first introduced in [23]. The value of 25000 is set such that  $k \sim 1$  is where the architecture is reasonably likely to achieve viability using the given architecture assumptions outlined in the Architecture Analysis chapter. A general equation attempting to capture some of the major driving parameters is shown in Equation 1.1.

$$k = 25000 P \eta s / c \quad (1.1)$$

where  $P$  is the selling price of space-generated power in \$/KWh,  $\eta$  is the efficiency of transmission to the ground,  $S$  (kWe/kg) is the specific power, defined as the power generated in orbit per unit mass needed in orbit to do so and  $C$  (\$/kg) is the launch cost to low earth orbit (LEO). In order to see the large improvements needed to approach unity values of  $k$ , our architecture focuses on finding innovative solutions to improving the specific power and end-to-end efficiency parameters.

## 1.3 Space Power Grid

Reproduced from [22]:

The Space Power Grid (SPG) systems architecture is an innovative, evolutionary approach to large-scale space-based solar power. The Experimental Aerodynamics and

Concepts Group at Georgia Tech has been working on the development of this architecture since 2006. The Space Power Grid architecture argues for three key technical architecture departures from traditional space-based solar power approaches. The first is to move to millimeter wave beaming at a frequency of 220GHz, as opposed to traditional microwave frequency choices at 2.45GHz or 5.8GHz. By moving to millimeter wave frequencies, the transmitter and receiver diameter sizes required come down to much more manageable levels, scaling the size of the spacecraft, and in turn the mass that must be placed into orbit, by a large amount. Traditional approaches have favored microwave transmission because microwave antenna and conversion devices have greater technological maturity and because frequencies over 10GHz experience poor transmission through rain and fog. Our architecture trades the technology risk of millimeter wave technology in favor of the greatly reduced system sizes. Potential options for transmission through rain and fog using millimeter waves include burn-through techniques, beaming around areas of high precipitation, and to consider using tethered aerostats placed above the weather generating portion of the atmosphere to receive the beamed power and then transmit it to ground via waveguides placed in the tethers.

The second key departure is the use of brayton cycle solar dynamic conversion of solar power, rather than photovoltaic arrays. The explanation for this trade is further detailed in the Brayton Cycle Turbomachine Design section of this paper. In order to reach the high power and intensities required for the high efficiencies of the brayton cycle, an optical concentrator system, the mirasol, is required. The design of the mirasol is discussed in the paper. The third key architecture change is to transmit from dynamic orbits around 2000km rather than from satellites placed in geosynchronous orbit. This also greatly reduces the antenna sizes required, bringing the spacecraft to much more manageable sizes.

Lastly, the Space Power Grid proposes a first phase that does not include space-based power generation. The initial phase would consist of a constellation of waveguide relay satellites that would serve as a power exchange with terrestrial power entities. Relaying power beamed from terrestrial power sites with excess power to high demand areas around the world. This key first step creates an evolutionary approach, with reasonably sized spacecraft (about 4000kg [24]) that can demonstrate and reduce many of the technical risks associated with a large scale space solar power architecture. This initial constellation would be replaced over time by the large gigawatt level spacecraft detailed in this paper.

## 1.4 Space Power Grid Development

In 2006, The Space Power Grid concept was introduced at the International Astronautical Congress in Valencia, Spain [25] and at the 2006 Space Technology and Applications International Forum [26]. A STK representation of the Space Power Grid was developed by Nicholas Boechler and is shown in Figure 1.1.

In 2008 and 2009, work progressed on the Space Power Grid by selecting parameters for the architecture [27] [28] [29]. A viability parameter to assess different space solar power architectures was established in [23]. This paper was presented at the 2011 IEEE Aerospace Conference in Big Sky, Montana.

At the 2011 International Space Development Conference in Huntsville, Alabama, the Space Power Grid team presented a paper that proposed a demonstration of a wireless power beaming relay utilizing collaboration between the United States and India [30]. The



Figure 1.1: Space Power Grid Beaming Representation

paper demonstrated that a space solar power demonstration was feasible using only a few relatively small satellites placed in Low-Mid Earth Orbit. This presentation also outlined the key differences in the Space Power Grid architecture from traditional approaches and began to shift the discussion among the space solar power community away from microwave beaming.

The Space Power Grid team presented three papers at the 2012 IEEE Aerospace Conference in Big Sky, Montana in March 2012. One paper detailed the design of a Phase 1 relay satellite using millimeter waveguides [24]. This paper showed that the design of these satellites had a mass that came in under 4000kg. A second paper conceptualized the design of the mirasol and girasol systems for the first time, detailing a gigawatt satellite design [31]. This paper introduced the Intensified Efficient Conversion Architecture (IECA) concept, in which brayton cycle solar thermal conversion of solar power was utilized. The final paper summarized the architecture and presented an analysis of technical feasibility and economic viability [32].

At the 2012 ISDC, the Space Power Grid team presented a proposal for a multinational collaborative demonstration of wireless power beaming. The team worked in collaboration with Ohio University Professor Don Flournoy. The accompanying paper was published in the Online Journal of Space Communication [33]. At the 48th annual AIAA Joint Propulsion Conference, the team presented a paper on the girasol design, discussing the use of brayton cycle heat engine for space solar power [34].

## Chapter 2

# Space Power Grid Architecture Summary

### 2.1 Millimeter Wave Beaming at 220GHz

The frequency selection is a key driver of the system mass of a space-based solar power architecture. This is because the antenna transmitter and receiver diameter sizes are a function of beam frequency and beam distance. The equation is derived from Fraunhofer Diffraction Theory. For capturing the primary lobe, which accounts for 84% of the power, the equation that relates transmitter and receiver diameter is shown in equation 1.

$$D_r = \frac{2.44R\lambda}{D_t} \quad (2.1)$$

The result is that for a given rectenna on the ground, the antenna diameter required for the transmitting antenna on the spacecraft is roughly 40x smaller than for a 5.8GHz system and roughly two orders of magnitude smaller than for a 2.45GHz system. Figure 2.1 shows a logarithmic plot comparing microwave, millimeter wave, and laser frequency selections at different beaming distances.

Historically space solar power architectures have generally selected microwave frequencies at 2.45GHz or 5.8GHz, as those frequencies have good atmospheric transmission. Glaser's architecture used 2.45GHz [35] and Mankins current SPS-Alpha project also uses 2.45GHz in its architecture [21]. The Halo concept studied as part of the the SERT program used 5.8GHz [36]. Devices for these two frequencies for space solar polar have been studied extensively [37] [38]. A millimeter wave based architecture has been proposed by Komerath [30]. Millimeter wave technology for space solar power applications was investigated in [39]. Laser SSP systems were investigated as part of the SERT program [36] and are being developed by JAXA [40].

Table 2.1 quantitatively summarizes the advantages and disadvantages of different frequency selections. Geosynchronous based architectures are forced to a frequency choice below 10GHz, as the fixed ground location and very large satellite size dictate the need for high atmospheric efficiency and transmission through all weather conditions. The small satellite size required for laser based architectures provides a significant advantage to the overall system mass and cost of these systems. However, poor efficiency values and existing treaties against the use of lasers in space led us to choose the millimeter wave regime for our architecture. There exists a good atmospheric transmission window around 220GHz in the millimeter wave regime that we have selected for our architecture. Millimeter wave beaming is seen as the best option by offering a compromise between the small system size of laser based architectures and the efficiencies achievable using

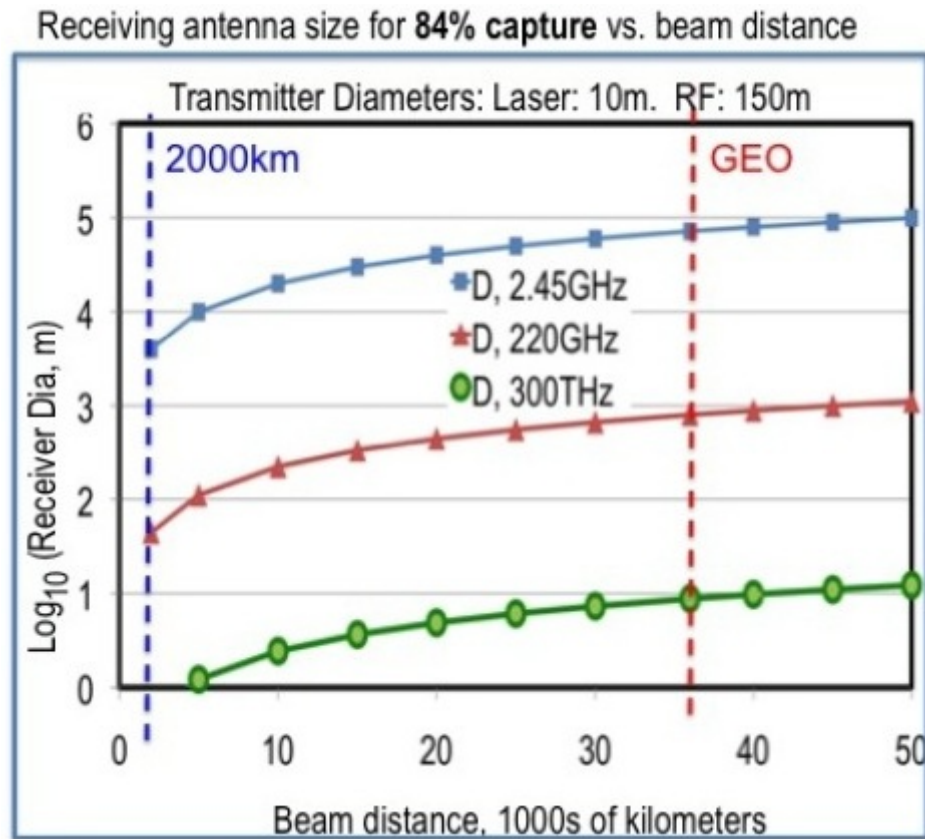


Figure 2.1: Comparison of Beam Frequency for 84% Beam Capture

microwave frequencies. There are two significant issues faced by millimeter wave architectures, achieving high efficiency of conversion to millimeter wave frequencies and transmission through poor weather. These items will be discussed in more detail in later sections.

## 2.2 Use of Brayton Cycle Turbomachine Conversion

In order to improve the specific power metric (kilowatts of electric power delivered to ground per kilogram required in orbit), brayton cycle turbomachine conversion is seen as a potential option for radical improvement. Traditional space solar power architectures have used large photovoltaic arrays, for conversion of solar power using photoelectric effects. However photovoltaic conversion does not offer favorable economies of scale at

Frequency Regime	Microwave	Millimeter Wave	Laser
Antenna Size	Highest	Low	Lowest
Atmospheric Efficiency	Highest	High	Low
Atmospheric Efficiency (Rain/Fog)	Highest	Low	Lowest
Conversion Device Efficiency	Highest	High	Low
Safety / Public Policy Concerns	Lowest	Low	Highest

Table 2.1: Comparison of Different Frequency Regime Architecture Choices



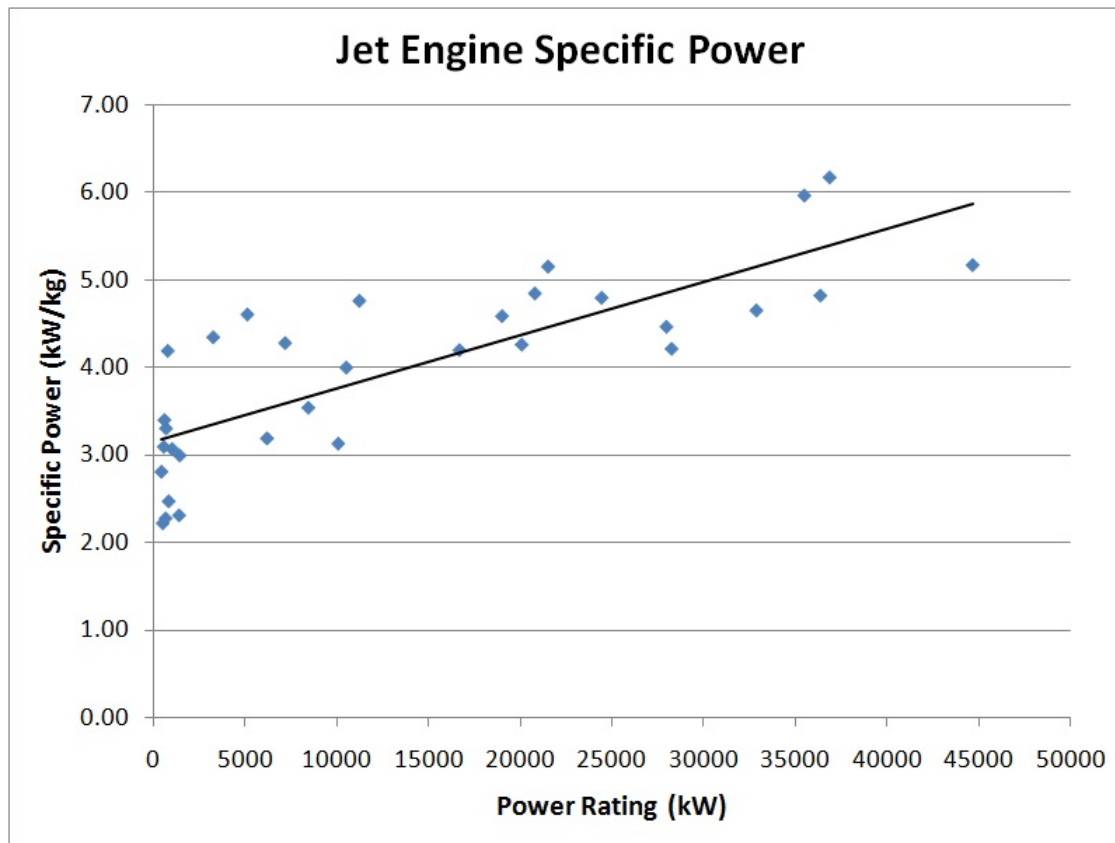


Figure 2.2: Specific power of commercial jet engines as a function of power level. Data for recent GE and Pratt and Whitney engines.

high power.

The option of intensifying sunlight and using high-intensity solar cell stacks in order to increase the power per unit area generated by photovoltaic arrays is limited because beyond an intensity of 2 Suns an active thermal control system is required [41] to remove and radiate out the waste heat. This implies that as intensity is increased to high levels, the active thermal control system more than nullifies any mass advantage gained by reducing converter area. Essentially, photoelectric effects do not exhibit good scaling trends because it is a surface-area based phenomenon. To increase the amount of power generated, the photovoltaic array needs a proportional increase in area. As a result, the amount of mass needed to produce each additional unit of power remains roughly equal at high levels of power.

On the other hand, Brayton cycle turbomachines used in aerospace propulsion do exhibit specific power values that rise with the level of power. Figure 2.2 shows data on mechanical power generated by modern jet engines. An approximately linear upward trend is observed in the figure. At the scale required for Space Solar Power, specific power above 10 kW/kg for conversion to mechanical power is achievable. For power levels over 50 MW, the specific power reaches 6 kW/kg [34].

A brief summary of brayton cycle conversion work being done at NASA Glenn is reproduced from [22], italicized below:

*NASA Glenn has researched the use of Brayton cycle converters for space power applications since the Brayton Rotating Unit development program dating back to the 1960s.*

*Currently, NASA Glenn has the 2kW Brayton Power Conversion Unit (BPCU) which has been tested and shown to work with nuclear fission heat sources [42]. The BPCU does not exhibit very high specific power because of its low power levels. In other words, it takes a lot more mass for a brayton cycle heat engine to produce its first watt than to produce its ten millionth for example. Mason argues for increasing specific power that can be achieved at high power levels in [43], offering favorable predictions for brayton cycle engine performance capabilities in the mid-far term.*

A high power brayton cycle heat engine operating at temperatures around 3500K could achieve the 80% thermodynamic cycle efficiency needed to achieve the desired efficiencies needed for a viable space solar power satellite. The greatly improved conversion efficiency over photovoltaic conversion systems has the large additional benefit of greatly reducing the thermal control system mass required to radiate the excess heat from power losses from the spacecraft. Conceptual gigawatt satellite design studies [31] [22] have shown the thermal control system mass to be a key driver of the overall satellite mass. Ultra-high temperature ceramic materials, such as Hafnium Carbide, have been identified that can achieve these temperatures [34]. An efficient ultralightweight radiator using graphene sheets has been proposed to reduce the thermal control system mass required [34]. Ultralightweight radiators have been studied at NASA Glenn by Juhasz [44] [45].

The overall result being that solar power satellites using brayton cycle conversion are shown to achieve specific power values that greatly exceed those shown for photovoltaic array based satellites. A 1 GWe Closed Brayton Cycle converter SSP satellite could potentially achieve around 1.5 kWe/kg, a significant increase over PV-based architectures that are shown to achieve up to 0.2 kWe/kg.

## 2.3 Orbit Location

Traditional architecture approaches have focused on geosynchronous orbits, as in Glaser's architecture [35] and the 1979 SPS Reference System [46]. Geosynchronous earth orbits (GEO) have the advantages of having a near continuous solar view. Additionally, the geosynchronous orbit means that vertical beaming is maintained fixed to a given ground location. The primary disadvantage is the large satellite size required for antenna systems beaming over such large distances (36000km). As a result, several more recent architecture proposals have moved down from GEO to Low or Mid Earth Orbits in an effort to reduce the overall size of the system, as proposed by Landis in [47] and in the Sun Tower architecture of the SERT program for example [8] [36].

Criswell has proposed beaming from the moon [48] [49]. The primary advantage cited for these architectures is that systems could be built using lunar materials and as a result much of the required mass would not be needed to be launched into orbit. Lunar space solar power is dismissed as a potential architecture choice in our analysis however, because the antenna sizes are driven to unrealistic sizes due to the large beaming distance from the moon to earth.

Our architecture argues to come down to 2000km orbits. Sun-synchronous dynamic orbits around 2000km are shown to have essentially continuous solar view in [50], as they orbit in a position along the Earth's Day-Night terminator. By coming down to this Low-Mid Earth Orbit location, required diameter sizes are brought down by an order of magnitude over there geosynchronous counterparts. Dynamic beam pointing from

these orbits is seen as a solved technical problem given modern phased-array antenna technology.

## 2.4 Power Exchange

As shown, the antenna system diameter required for geosynchronous systems based off of the beam frequency and beaming distance is on the order of kilometers in size. This dictates that to launch just one of these satellites very large mass and in turn launch costs are required. Thus, there is no evolutionary path seen to GEO-based microwave solar power satellites. This creates a large cost to first power barrier to jump-starting the move towards space-based solar power. No government or private entity is willing to commit the billions necessary upfront given the technical risks of setting up a large space-based infrastructure project.

The SPG architecture argues for an evolutionary approach to space solar power by establishing a power exchange among terrestrial energy sources. The first phase of the Space Power Grid does not include space-based power generation, but rather it establishes space as a dynamic power grid. Here the idea is to use space for synergy with terrestrial power sources. This phase consists of millimeter waveguide relay satellites that generate revenue by using space as a means of power exchange. By beaming power from locations with excess supply to locations with high demand, this phase provides early revenue generation. It also helps make terrestrial solar and wind more viable and more environmentally friendly because of the inherent intermittency associated with solar and wind. Solar and wind power plants have fossil fuel based auxiliary generators in order to be able to provide baseload power. By establishing a space power grid that can beam power in intermittent periods, the need for these fossil fuel based generators diminishes. The ability to beam power “anywhere, anytime” and the ability to beam to remote locations such as desert islands or forward military bases, where the cost of power is high, allows this phase to charge a premium for the power that it delivers, allowing this phase to breakeven within 17 years using our economic model. These relay satellites, with the capability of beaming 60 MW, are very moderately sized satellites around 4000kg each that are capable of easily being launched by current launchers. Thus, the investment cost of launching these satellites is miniscule compared to launching space-based power generating satellites. However, it offers a crucial step by illustrating the potential for space power beaming and reducing many of the beaming technology risks associated with large scale SSP. Additionally, it establishes an infrastructure of ground facilities ready to handle delivery of SSP, once large power generating satellites are put into place.

## 2.5 Architecture Summary

A summary of the architecture is shown in Figure 2.3 and in Figure 2.4. At project start, there is initially a six year research and development phase for technology maturation. At this point, 4000kg class phase 1 relay satellites are launched. The phase 1 constellation of approximately 100 satellites, placed at an altitude of 2000km establishes the power exchange outlined in the previous section. These satellites would relay power to/from antenna sites on the ground and to lighter than air platforms placed at an altitude of about 4000m. This altitude allows the millimeter wave power to be sent from the tethered

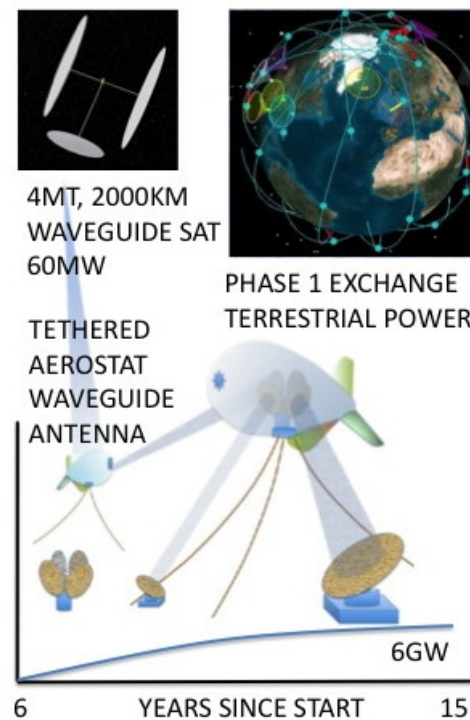


Figure 2.3: Timeline of Phase 1 of SPG Architecture.

aerostats through waveguides located in the tethers to the ground. Each of the satellites is capable of transacting 60MW power. Thus by the time the constellation has grown to 100 satellites by year 15 from project start, the grid is capable of exchanging 6GW of power.

While the Phase 1 satellites are being deployed, the gigawatt class phase 2 satellites are being developed concurrently. This includes the girasol gigawatt converter satellites and the mirasol ultralight collector/concentrator mirrors. These satellites would begin to be deployed roughly 17 years from project start. In order to reach multiterawatt level space solar power, routine space access is needed in order to launch the required mass into orbit. The development of a runway-based space access system is seen as a necessary requirement for this and any space solar power architecture to launch the required mass for large-scale SSP. According to our economic analysis, the SPG architecture can provide 4TW of power and contribute a significant portion of power to satisfy the world's growing energy demands, reaching breakeven using reasonable assumptions by year 40 if a runway based space access system is developed that can launch 140,000MT/year. SSP is one of the few markets that might be able to justify the large investment in the development of a runway-based space access vehicle capable of routine operations [51].



Figure 2.4: Timeline of Phase 2 of SPG Architecture

## 2.5. ~~ARCHITECTURE SUMMARY~~ SPACE POWER GRID ARCHITECTURE SUMMARY

# Chapter 3

## Proposed Demonstrations as a First Step

### 3.1 Demonstration Objectives

A wireless power beaming demonstration is seen as a necessary first step in moving towards large scale space solar power for several reasons. A wireless power beaming demonstration from space would significantly reduce the technological uncertainties of a space solar power architecture and help generate necessary support from industry, government entities, and the general public. Such a technology demonstration could be performed in the near term to jump start the path towards large-scale space solar power.

Several demonstrations have been proposed. In 2008, Seth Potter, John Mankins, and others presented a proposal to conduct an experiment using the International Space Station [14]. This experiment would use a 100kW power plug satellite to beam power to forward military bases. The demonstrator satellite would use a solar array similar in size to the Integrated Energy Assembly (IEA) module of the ISS. Potter also presented a proposal to use a 94GHz converter on the ISS to beam 10kW to receivers at the Goldstone Observatory in California and also to locations in Australia and Florida [52]. Both Japan and China have already proposed plans to conduct Low Earth Orbit demonstrations of wireless power beaming in the near-mid term [18].

Specific objectives of a demonstration are reproduced from [33]:

#### Scientific Objectives

1. Global propagation data and optimal frequency: At present, public-domain data on millimeter wave propagation through the atmosphere are mostly from a few locations above astronomical telescopes as in Ref. [53]. These are typically located at high altitudes or in deserts. A comprehensive database from numerous locations around the world can be obtained with beaming conducted from International Space Station and from a polar-orbit satellite as proposed later. The approximate locations of favorable transmission windows in the frequency regime are known. By sweeping through fine-tuned frequency windows within these primary windows, the best frequencies can be identified, and optimized through global propagation characteristics.
2. Sources of losses: Precise sources of propagation losses will be identified from using the data from the frequency sweep. These are expected to include absorption of energy into water, oxygen and nitrogen molecules, refraction and scattering through

the ionosphere and through density gradients, and scattering by water and dust particles.

3. Nonlinear interaction between beam and atmosphere: Most applications to-date requiring millimeter wave propagation data, have been either at low power, such as for astronomical observations or communication signals, or for pulsed transmission. The problem of continuous power delivery to or from a ground receiver opens a new regime, where the beam transits the lower atmosphere for several minutes, at a power level of over 50 MW. This opens several possibilities where the first few seconds of power transmission may be sacrificed to clear a highly efficient transmission path. Alternatively, part of the power may be directed to a different set of frequencies intended to saturate or otherwise neutralize the energy levels of molecules or particles that otherwise absorb energy at the primary frequency. These options remain to be investigated, and promise a rich harvest of science and engineering innovation.
4. Health Issues: A very strong purpose of the proposed experiment is to understand health risks associated with high-power millimeter wave reception at the ground. How much scattered radiation poses danger to people, and whether these risks if any, can be eliminated, are important topics of research.
5. Conversion to and from millimeter waves: Large-scale conversion to and from millimeter waves, and the development of converters with high specific power and efficiency are high-priority items for research. Today the best option for high power is still to use gyrotrons. Solid state systems exist for low power applications, and promised high efficiency, but it is not clear what happens if they are scaled up to Megawatt levels. Radically different options may be appropriate for the high power, continuous-beam application where efficiency and mass-specific power are of critical importance. One is the option of directly converting solar energy to beamed millimeter waves using optical antennae, without passing through a direct current stage. Another is to generate a relatively high frequency of electric power (possibly in the MHz range) rather than the traditional 50 or 60 Hz, and use this to generate millimeter waves (220 GHz) more efficiently. A third is to use some form of electro-optics in solid state MMICs with high efficiency, thereby minimizing the need for chip cooling, and allowing efficient scaleup.

### Technology Demonstrations

Certainly, the ISS experiment will provide an actual demonstration of solar-generated electric power being received at Earth. In this case the actual collection and conversion will be performed by the existing solar panels and power conditioning systems of the ISS, but the rest of the system poses several opportunities for technology demonstrations. Dynamic beaming, where the beam pointing is adjusted in real time based on feedback from atmospheric propagation errors, is an issue that has apparently been solved in the military community, but is still a mystery to many people including much of the Space Solar Power Expert community. Thus it is an essential item for public demonstration. Similarly, the idea of starting and stopping transmission as the link is established and removed, with safeguards, needs public demonstration. The challenges of integrating such unsteady power reception at high power levels into the terrestrial grid appear steep, but recent work shows that the necessary knowledge and infrastructure are already in place or



can be added quickly with today's Smart Grid initiatives. A demonstration of reflecting or guiding a high-power beam from a terrestrial transmitter, through a satellite and onto another terrestrial receiver located beyond the horizon, is also essential, for people to see Space as a viable place for a power grid connecting renewable power plants on different sides of the globe. These are just a few examples of the technology demonstration opportunities. A summary list of technical demonstrations is given below:

1. Low-mass antenna design for millimeter waves;
2. Low-mass, resonant millimeter waveguides;
3. Conversion from solar-generated DC to millimeter waves;
4. Dynamic pointing accuracy, with adaptive refinement;
5. Beam capture efficiency/safety;
6. Conversion from millimeter waves to useful terrestrial power;
7. Power grid aspects of dynamic beaming;
8. Capture of terrestrial power at spacecraft;
9. Reflection/ waveguiding of terrestrial power through spacecraft to in-space target;
10. Retail beaming;
11. Aerial platforms for transmission and capture;
12. Waveguide tethers; and
13. Beamed propulsion

### Public Policy

The current United States National Space Policy lists expanding global cooperation as one of the nation's top three space-related goals [54]. Terrawatt level SSP will require large infrastructure investments that can only be made viable with global participation. The ISS is a noteworthy example of the benefits of global collaboration in Space. As a cooperative effort itself, the ISS seems a logical platform for extending global collaboration in space to a wireless power beaming demonstration effort. On the other hand, the experiment will provide an opportunity for lawmakers and government officials, as well as the electorate, to gain experience in dealing with the many issues of power beaming, collaboration between renewable power plants, Smart Grid access, land use for millimeter wave receivers, balancing security and economic development in advancing the technology of millimeter wave beaming and other issues. To the interesting policy issues generated by the multinational International Space Station venture, and the Global Positioning System, we must now add exchange of power and use of high-power, continuous beaming between nations. The proposed missions provide low-risk endeavors to deal with these issues without incurring large delays during a full-scale deployment effort.

## Public Education

Public acceptance is perhaps the most critical step in enabling the development of Space Solar Power Systems, as argued in Ref. [55]. Currently, Space solar power is not widely known amongst the general public or even among the more general scientific or academic communities. The general public is eager to learn and embrace potential alternative energy solutions. However, when presented with the idea of wireless power beaming from Space, the majority of the public is likely to respond with concerns regarding feasibility, costs, and public health and safety issues. The proposed demonstration would serve as a means of informing to the general public that space solar power is a feasible alternative, while reducing fears about adverse health effects.

Public education has specific objectives:

1. Answers to why space solar power is important, and why the multinational experiment is a good start towards it.
2. How space solar power can be brought about, and how long it will take.
3. What can and must be done in the near future to make this happen.
4. Why we must start today to reach success in 15 years.
5. What is the realistic risk? What are the payoffs?

Public perceptions of health and safety issues can be just as critical to bringing about space solar power as public health and safety issues, as noted by Pignolet et al.[56]. Pignolet claims that SSP technologies have no ionizing effect, and thus present no risk of causing cancer from microwave radiation. The other major safety concern expressed from the public is what happens if you were to go through this beam or what happens if the beam moves off target and a high-power beam hits populated areas in a city. There are standard safety features in any electrical system to prevent such occurrences. In the case of power beaming, the minimum expectation is that there is always a low-level pilot beam establishing a 2-way link, and this link must be working very well with no interruptions or degradation for the main power beam to be on at all. The switching off can occur in picoseconds. The proposed demonstration would quell these fears by demonstrating technology such as retrodirective beam pointing, in which a small amount of power is sent from the ground rectenna to confirm the link with the solar power satellite, ensuring the beamed power does not miss its targeted receiver on the ground. Additionally, the power density of the beam should be small enough to be well within levels considered safe for limited exposure time. A demonstration of this kind would allow detailed data to be collected on power densities at the rectenna and surrounding the rectenna site.

## Build Momentum

A visible, functioning multinational demonstration working for several years generating useful science, technology and measurable progress towards full implementation of Space-based Solar Power would build momentum towards encouraging space solar power development. This is especially true because we have a roadmap towards full-scale development and deployment of Space Solar Power, and the proposed experiments are real technology demonstrators that pave the way along this road.

## 3.2 US-India Power Exchange

Significant interest has been shown between the United States and India in using space solar power in establishing a strategic partnership to pursue space-based solar power as outlined by Garretson [57] and with the announcement of the NSS-Kalam initiative [58]. India has shown considerable interest in moving towards non-renewable energy sources to feed explosive growth in the demand for power in India and improve the current infrastructure which is inadequate to meet growing energy demands. This immediate demand creates a unique opportunity to establish a space solar power demonstration using the United States and India that can satisfy the objectives of a demonstration as outlined in the previous section. STK simulation models were created to illustrate that a power exchange demonstration between the United States and India could occur using a small number of satellites and ground facilities. The demonstration options modeled were presented at the 2011 International Space Development Conference in Huntsville, Alabama. These options are summarized and reproduced from [30] below:

### 4-Plant Model

A demonstration model has been created using the Satellite Tool Kit (STK) using up to six satellites and up to four facilities. The satellites have a near equatorial orbit with an inclination of 15 degrees and an altitude of 5500 km above Earth, and have evenly spaced right ascension of the ascending nodes. Using the four facilities in our demonstration, United States (New Mexico, near Las Cruces), India (near Mumbai), Egypt (near Cairo), Australia (Western Australia) this model provides 24 hour continuous beaming to all plants. This orbit was chosen because the satellites never drop “too low” on the ground path to be seen by our chosen demonstration model facilities. The satellites are continuously in sight of each other, and at the same angle, meaning that no pointing is necessary for continuous space to space beaming. The low inclination angle that is relatively close to the latitude at the launch site (Cape Canaveral, FL) keeps plane change delta-v costs low. Figure 3.1 illustrates the four plant model.

### US-India 2-Plant, 6-Satellite Model

The demonstration model has been reduced to a two facility US-India model. Our model has essentially 24 hour continuous beaming, with a very small period of downtime that results because the two plants are not on exactly opposite sides of the Earth. Beaming in green represents New Mexico beaming to Mumbai; beaming in red represents Mumbai beaming to New Mexico. The model also has short periods of downtime that exist when the system is transferring from one 3-satellite chain to another.

Other variations of the US-India Model have been considered. Using a 3-satellite configuration at the current altitude (5500 km), there was very little time for beaming. Even extending the 3 satellites to 10000 km did not allow reducing the number to 3. We also looked at a 6-satellite configuration at 10000 km and it eliminated the gaps that the 5500 km version has when switching between satellites. In fact there is some overlap where one only needs to do beaming from one satellite to another satellite and back to Earth. Therefore, the ideal altitude for this startup demonstration with minimal number of satellites and ground stations, is somewhere between 5500 and 10000 km. Once the number of satellites increases, newer satellites will be placed as low as possible, which is probably at 2000km or even lower.

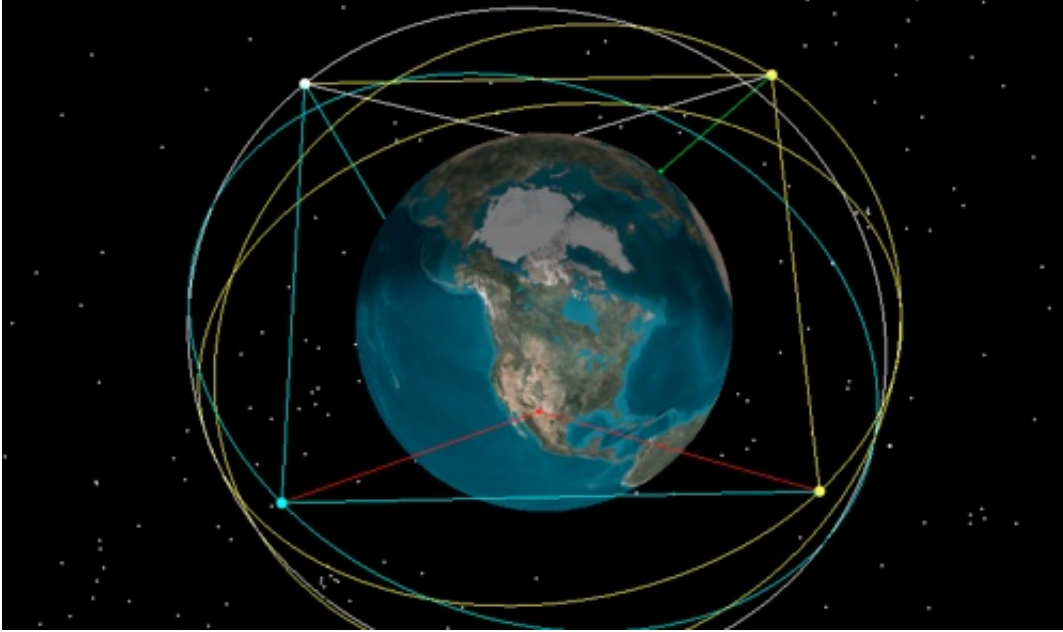


Figure 3.1: STK Simulation of a 4 plant US-India Power Exchange Demonstration

The 6-satellite, 2 facility model has continuous 100% beaming (shown in Figure 3.2). The 4-satellite, 4 facility model has continuous 100% beaming for inclinations between 0-6 degree inclination. As a result, the inclination of our orbits in our model has been changed to equatorial. At 15-degree inclination, the New Mexico plant could receive beamed energy about 95% of the time.

These results are presented only for demonstration purposes, consistent with the basic research / initial concept exploration charter of our university research group. As the engineering of the demonstration model matures, surely other optimal configurations will become evident, with performance superior to what we present. For instance, the best locations for terrestrial plants in India may not be near humid Mumbai (Maharashtra) which receives heavy monsoon rains for several months, but perhaps in the Thar desert of Rajasthan, or the arid high plateaux of the Deccan in central India. The advantages of global collaboration cited by Dr. Abdul Kalam, former President of India, are brought home by the immediate advantage in number of satellites required to achieve continuous beaming, when more nations are included. Australia, Japan, New Zealand, the north African desert nations, the desert nations of the Middle East, the deserts of southwest Africa, parts of Russia, Chile, Argentina, Greenland, Iceland, island nations in the South Pacific, are all excellent candidates.

### 3.3 Five Nation Demonstration Proposal

At the 2012 International Space Development Conference in Washington DC, a multi-national wireless power transfer demonstration was proposed as a critical step on the road towards space solar power. A mission architecture involving the International Space Station and a second relay satellite would be used to demonstrate millimeter wave power beaming. An STK simulation of the proposed demonstration is shown in Figure 3.3. The proposal seeks necessary buy in from several entities, as follows (reproduced from [33]):

1. National space agencies. Most national space agencies of the space-faring nations

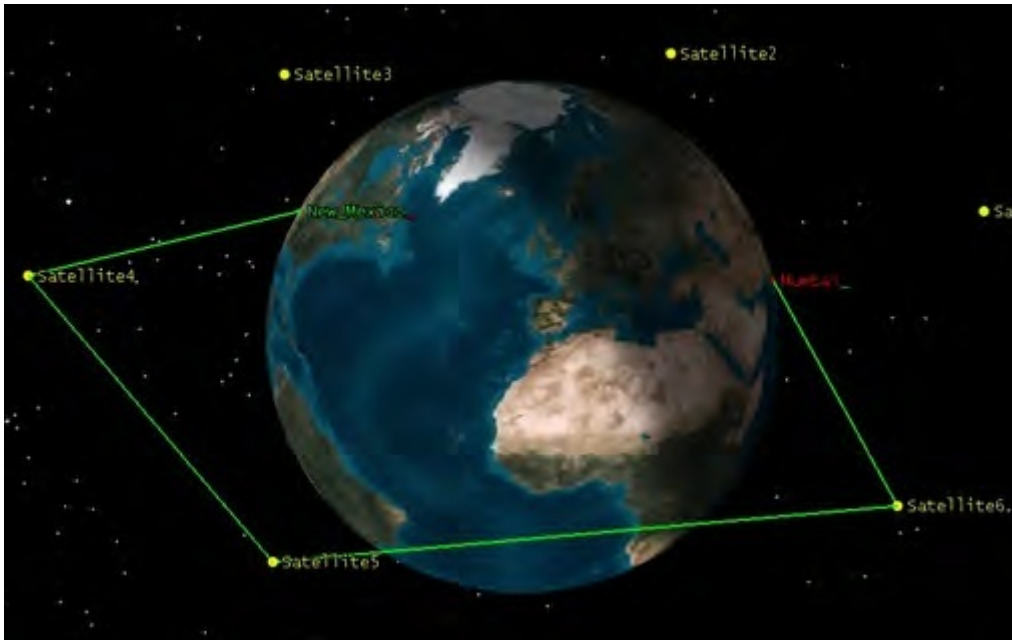


Figure 3.2: Six satellite, two-plant model to start a direct power exchange

are mandated to seek scientific payoff as well as technology advancements. The dynamic beam pointing and atmospheric propagation issues of millimeter waves are appropriately worthy of their attention, the latter being also of interest to the astronomy community. There is considerable interest in understanding millimeter wave propagation through the lower atmosphere, as well as through the ionosphere. The proposed mission will conduct a high-resolution sweep of the frequency regime in each of the selected frequency windows, and continue the measurements for several months to collect a comprehensive database. These data will enable accurate projection of end-to-end efficiency and reliability of SSP at a utility scale.

2. Terrestrial energy industry. The mission will help develop a Space-based power exchange where terrestrial plants can buy and sell power to adjust to demand in real time. This is a way to boost the business case of terrestrial renewable power plants in the near term, leading to quick growth in terrestrial renewable energy supply.
3. The electronics/communication industry. The mission will develop the field of high-power millimeter wave generation, conversion and transmission, with the immense market potential of SSP and Space-based power exchange.
4. Space transportation industry. One strong area of interest and concern is in the development of runway-based Space Access. SSP is viewed as one of the few markets large enough to justify investment in large airbreathing space access vehicles that offer airline-level regularity and frequency of operations. In turn, such operations are essential if SSP is to achieve the drastic reduction in launch costs needed for viability.
5. Military agencies. The mission will help develop a collaborative regime where militaries can co-develop technologies of mutual interest.

### 3.3. FIVE NATION PROPOSED DEMONSTRATIONS AS A FIRST STEP

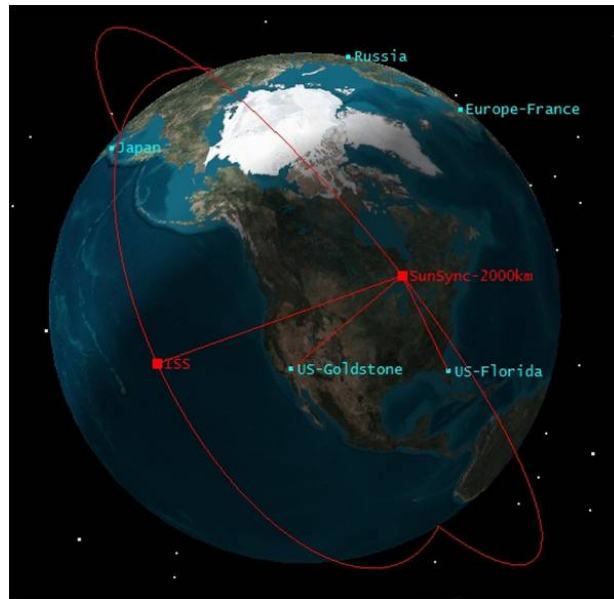


Figure 3.3: STK Simulation of Proposed Five Nation Demonstration Over The United States

6. General public interest in SSP: The support and interest of these diverse entities is key to generating the momentum that can take us towards full-scale Space Solar Power.

# Chapter 4

## Power Exchange using Relay Satellites

### 4.1 Millimeter Waveguide Relay Satellite Design

The conceptual design of a Phase 1 Space Power Grid relay satellite was designed in [24]. The proposed satellite was designed to receive beamed power and transmit it through the waveguide subsystem to a transmitting antenna for beaming to another spacecraft or to ground. The goal of the spacecraft design was to develop a design that would meet the requirements of the Space Power Grid Phase 1 architecture by minimizing spacecraft mass and maximizing efficiency.

#### 4.1.1 Antenna Transmitter and Receiver Diameter Equation Derivation from Diffraction Theory

In the frequency selection section, the relationship between antenna transmitter and receiver diameter was first introduced for capturing the primary lobe of the diffracted beam. Here, more detail into where this equation comes from is shown, to justify more than 84% beam capture for the Space Power Grid. A table summarizing the amount of power captured by each ring of the airy disc diffraction pattern and the constant value required for the diameter relationship equation is shown in Table 4.1.

Reproduced from [24]:

The antenna transmitter/receiver diameter relationship comes from the fundamental limit to resolution, diffraction. The derivation of this relationship is given in standard textbooks on diffraction theory. Fraunhofer Diffraction at a circular aperture can be represented using a Bessel function of the first kind [59]. The amount of power received is calculated from this in the Rayleigh Limit[59]. The results are shown in Figure 4.1. The three data points correspond to the first three rings of the Airy disc. Using the transmitter and receiver diameter relationship for different fractions of power received gives Figure 4.2. This plot shows the results of capturing the first three rings on power received. An additional data point shows that in order to receive 98.5% of the transmitted power, an order of magnitude increase in this constant value is required. These plots show the design challenge traditionally faced by antenna designers. For radar and communications applications, designers optimize by choosing to receive only the central lobe (84%). This practice, which is immensely wasteful for power beaming applications, has been assumed in most Space Solar Power architectures that use GEO and low microwave frequencies,

Airy Ring	% Power	$J_1$ Zeros	$k_R$	$k_D$
1st Ring	83.8	3.8317	1.220	2.44
2nd Ring	91.0	7.0156	2.233	4.47
3rd Ring	93.8	10.1735	3.238	6.48
4th Ring	95.2	13.3237	4.241	8.48
5th Ring	96.1	16.4706	5.243	10.49

Table 4.1: Values for Diffraction of Beam

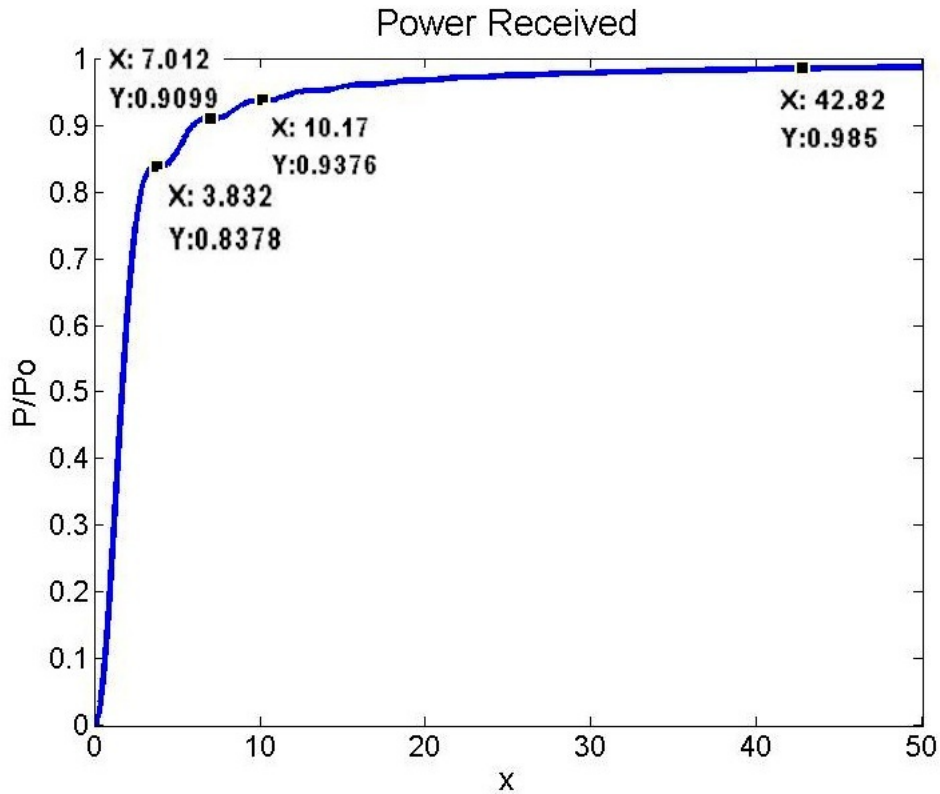


Figure 4.1: Amount of Power Received in terms of  $x$  from Bessel Function of the first kind

because the antenna size is already close to being prohibitive there. With the choice of 2000 km altitudes and 220 GHz frequency, the designer can have the luxury of specifying at least 95 % capture.

#### 4.1.2 Relay Satellite Waveguide Subsystem

Reproduced from [24]:

The waveguide system is designed to transmit power from a receiving antenna of the satellite to a transmitting antenna with minimum losses. Any power losses from the waveguide system adds heat to the spacecraft that must be radiated from the spacecraft, driving the mass of the thermal control system. Corrugated waveguide structures can be designed to transmit power in the millimeter wave frequency range around 220GHz in a near lossless manner[60].

General Atomics produces straight corrugated waveguides with very low losses in the



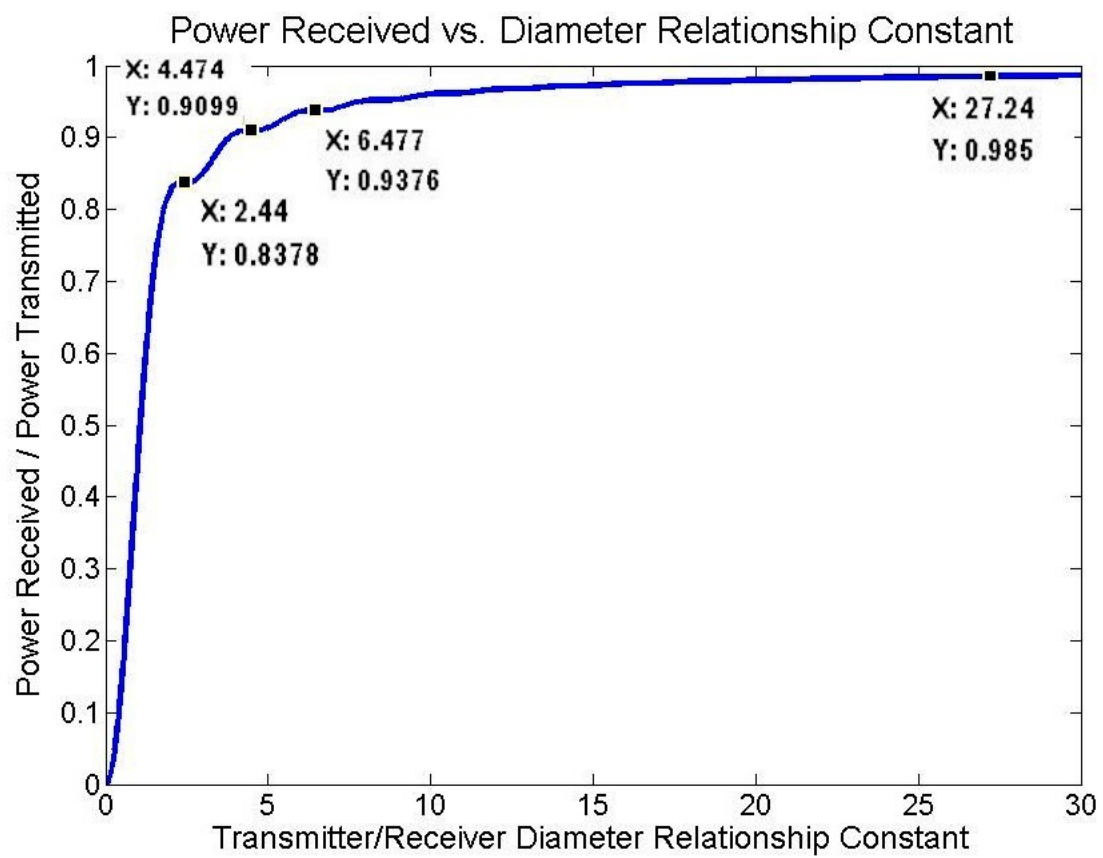


Figure 4.2: Amount of Power Received in terms of the constant relating transmitter and receiver diameter

HE<sub>11</sub> mode[61]. General Atomics produces corrugated waveguides at a number of frequencies with a diameter of 31.75mm and a diameter of 63.5mm. As frequency increases, attenuation decreases exponentially until the frequency reaches the region where Bragg scattering can occur[61]. For a frequency of 220GHz, the 63.5mm diameter waveguide has a near zero attenuation loss. An example of what the corrugated waveguide structure looks like can be found on the General Atomics website[61].

The waveguide system consists of two waveguides. One connecting the space to space antennas through the spacecraft, and the other connecting the space to space antennas to the space to ground antenna. The antennas were placed sufficiently far away from the spacecraft body such that the radiated heat from the thermal control system would not heat the spacecraft body. This drives the values for length shown in the table. The material chosen for this design is copper due to its conductive properties and because it is inexpensive.

The waveguide system is capable of transmitting large quantities of power by leveraging the fact that space is a vacuum. The amount of power a waveguide can transmit is limited by the Electric Field Breakdown Limit of the medium[62]. The electric field breakdown limit in a vacuum is an order of magnitude higher than that of air. The values for width, depth, period, and diameter that define the corrugated structure of the proposed waveguide system shown in Table 4.2 match the 63.5mm corrugated waveguide produced by General Atomics.

Efficiency through the waveguide was assumed to be 99% because of the near zero attenuation losses of the corrugated waveguide. Estimating a 1% efficiency loss at the transmitting antenna junction and receiving antenna junction, a total waveguide system efficiency was estimated to be 97%. Using the design power of 60MW, this results in a loss of 1.8MW of power that must be radiated away from the spacecraft as heat. Using a nominal wall thickness value of 2mm, a system mass was estimated to be roughly 70kg.

### 4.1.3 Relay Satellite Summary

A conceptual diagram of a relay satellite is shown in Figure 4.3.

Table 4.3 shows a mass summary breakdown of the different satellite subsystems. Subsystem mass value were designed using traditional spacecraft design practices as outlined in [63].

Table 4.4 shows an end-to-end efficiency analysis of beamed power relayed from the ground to a relay satellite, to another relay satellite, before being beamed to another ground location.

## 4.2 Tethered Aerostats

As a potential solution to the issue of poor atmospheric attenuation of millimeter wave frequencies, incorporating Lighter Than Air Platforms (LTAs) into the architecture is proposed. Our architecture places tethered aerostats at an altitude of 4000m. This altitude places the platforms above the weather generating portion of atmosphere. Efficient corrugated waveguides placed inside the tethers would transmit the millimeter wave power to the ground. Figure 4.4 shows a conceptual drawing of an aerostat. In [64], LTAs were proposed as a means of power beaming, with one possible application including using the aerostats in conjunction with a space power beaming architecture. Laser SSP

Parameter	Value
Length Waveguide 1 (m)	18.5
Length Waveguide 2 (m)	20.3
Total Length (m)	38.8
Material	Copper
Medium	Vacuum
Mode	HE <sub>11</sub>
Corrugation Period (mm)	0.66
Corrugation Width (mm)	0.46
Corrugation Depth (mm)	0.41
Diameter (mm)	63.5
Frequency (GHz)	220
Max Power Transmitted (MW)	60
Attenuation (dB/10m)	0.001
Efficiency Through Waveguide	0.99
Efficiency Waveguide-Antenna Junction	0.99
Total System Efficiency	0.97
Power Loss (MW)	1.8
Density Material (g/cm <sup>3</sup> )	8.94
Wall Thickness (mm)	2
Mass/Unit Length (kg/m)	1.81
<b>Mass (kg)</b>	<b>70.3</b>

Table 4.2: Waveguide System Properties

Subsystem	Mass (kg)
Payload (3 antennas)	734.3
Propulsion	75.0
Attitude Control	179.6
C & DH	64.3
Thermal	989.0
Electrical Power	774.5
Structure and Mechanisms	570.9
Waveguide	70.3
Communications	64.3
<b>Total Spacecraft Dry Mass</b>	<b>3422</b>
Dry Mass w/ Contingencies (kg)	3757
Propellant Mass (kg)	510
Loaded Mass (kg)	4267
Spacecraft Volume (m <sup>3</sup> )	17.73
Spacecraft Diameter (m)	2.5

Table 4.3: Relay Satellite Mass Summary

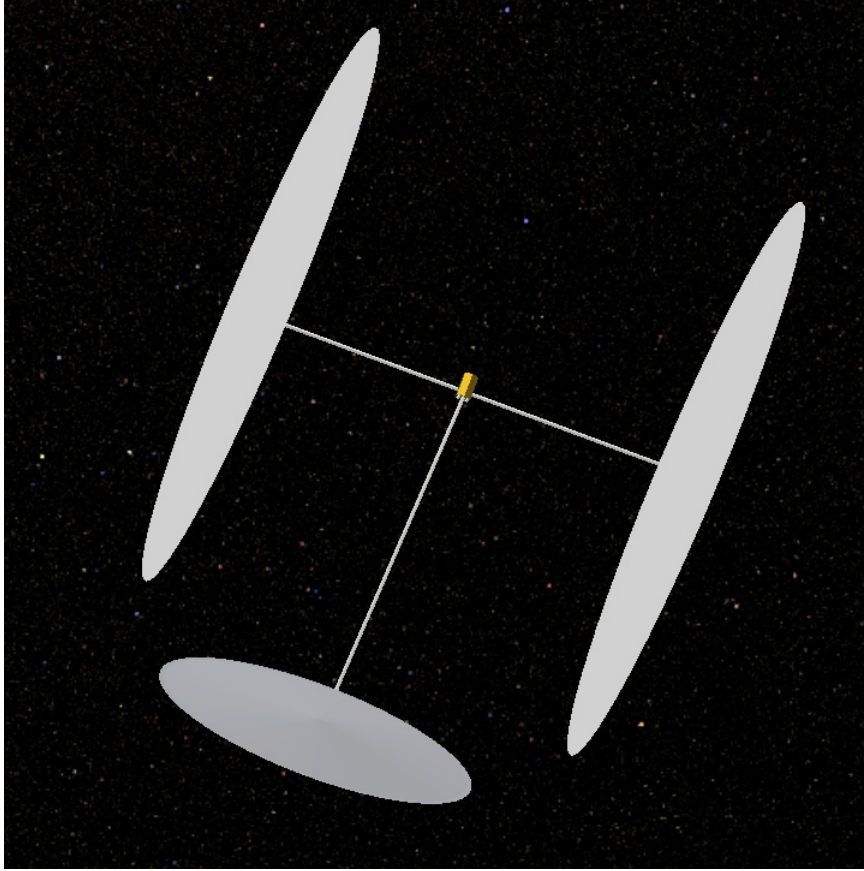


Figure 4.3: Millimeter Waveguide Conceptual Design

Parameter	Value
Efficiency through Atmosphere	0.90
Ground Receiver Capture Efficiency	0.95
Satellite Receiver Capture Efficiency	0.95
Space Receiver Antenna Efficiency	0.90
Space Transmitter Antenna Efficiency	0.90
Efficiency of Waveguide System	0.97
Total Spacecraft Efficiency	0.79
<b>End-to-End Efficiency</b>	<b>0.43</b>

Table 4.4: Summary of Relay Satellite Efficiency Values

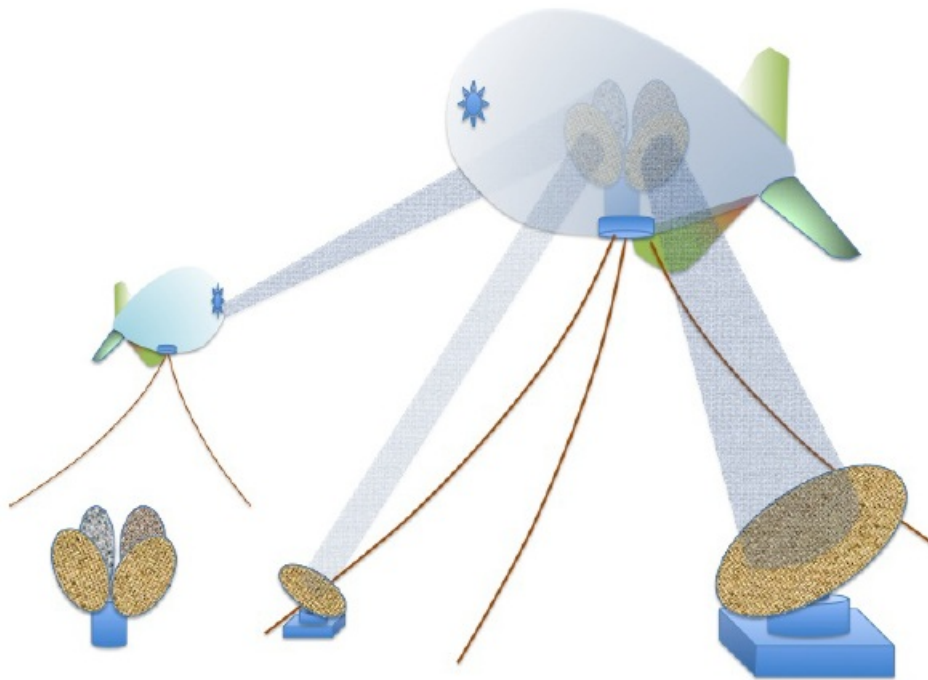


Figure 4.4: Conceptual Drawing of Aerostat

systems have also suggested the use of tethered aerostats as a potential solution to the atmospheric efficiency and safety concerns associated with these high frequencies [65].



# Chapter 5

## Gigawatt Satellite Design

The major mass components of the SPG architecture are the gigawatt satellite systems of phase 2, consisting of two parts. The girasol satellite consists of the brayton cycle turbo-machine conversion aspect of the system. The mirasol is an optical collector/concentrator that uses an array of individually pointable optical elements to concentrate solar energy to the intensified feed target of the girasol satellite. The mirasol-girasol gigawatt system of concentrating solar power via the mirasol satellite and converting solar power via the girasol satellite for beaming, we call the Intensified Efficient Conversion Architecture (IECA) concept.

A conceptual drawing of the girasol portion of the gigawatt satellite, receiving concentrated sunlight from a mirasol, is shown in Figure 5.1.

### 5.1 Orbit Options

Reproduced from [22]:

The mirasols are required to concentrate solar power to the heater of the brayton cycle heat engine. The mirasol and girasol aspects of the spacecraft are not physically connected and there are multiple options considered for the orbit placement of the two parts, outlined in this section.

1. Place the mirasols as high altitude collector/concentrators: In this option, the mirasols would be placed at an altitude around 20,000km or higher and reflect/concentrate power down to the LEO constellation of girasols. This option has the advantage of being able to easily reach all parts of the globe and maintain near constant solar view. This option is limited however by the spot size issue of reflecting solar power over such large distances [50]. Thus, the area of the girasol collector dish would have to be increased substantially for this option over the current design.
2. Place mirasols and girasols together in sun-synchronous dynamic orbits: This option has the advantage that the spot size issue is eliminated while constant solar view is maintained, and the collector dish of the girasol is no longer a necessary component of the spacecraft. Spacecraft placed in sun-synchronous orbits around 2000km can maintain constant solar view by staying along the Earth's day-night terminator as identified by Potter and Davis [50]. The issue with this option is the ability to continuously beam to the dark side of the Earth.

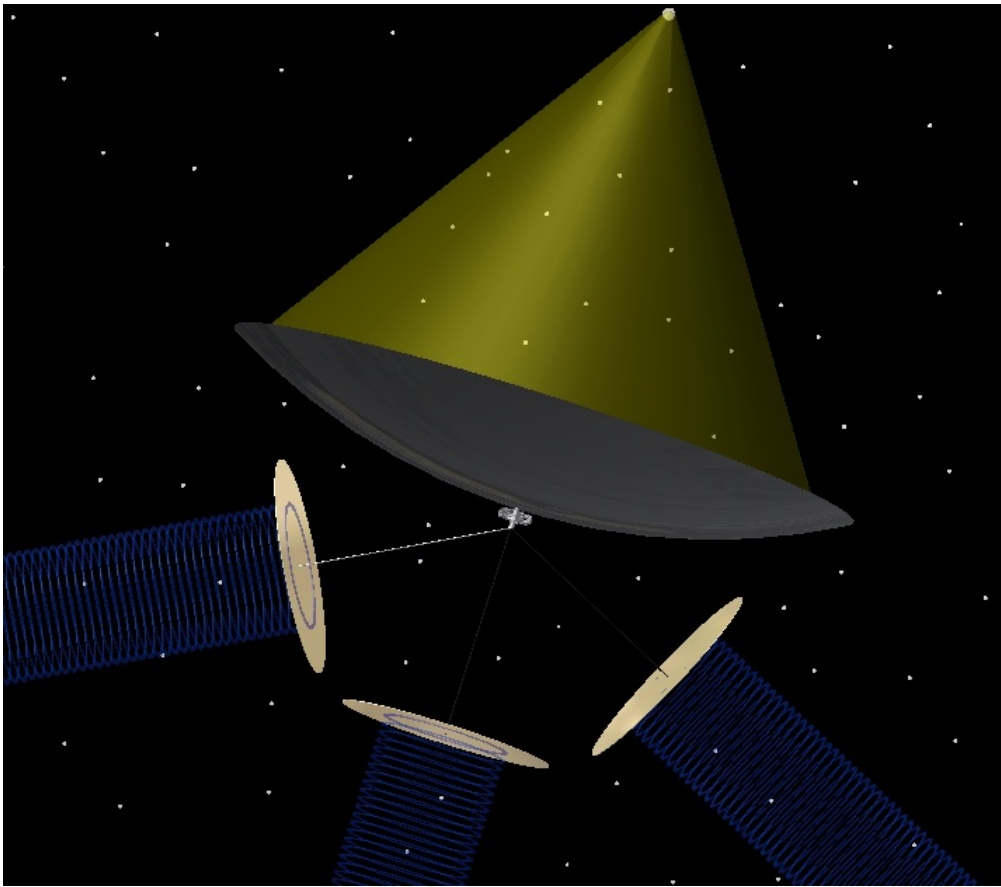


Figure 5.1: Conceptual Drawing of Girasol



3. Place mirasols and girasols in close orbits at 2000km: This solution allows for a compromise between the other two options. Although the girasol still requires a collector dish, the mirasols, placed predominately in sun-synchronous orbits, beam to nearby girasols in orbits around 2000km altitude. The result is that the spot size is small enough to be at manageable levels, while continuous beamed power delivery can be achieved to the dark side of the Earth.

## 5.2 Girasol Design

### 5.2.1 Satellite Configuration

Figure 5.2 shows a labeled schematic (not to scale) indicating the different components of the girasol satellite. The numbers in Figure 5.2 denote:

1. Collector
2. Intensified feed
3. Heater
4. Compressor
5. Turbine and Generator
6. Radiator
7. Phase Array Antenna

In order to achieve the 80% cycle efficiency required, operating temperatures around 3500K are required. Ultrahigh temperature ceramic materials that can withstand these temperatures, such as Hafnium Carbide, are proposed for the design.

### 5.2.2 Cycle Analysis

Table 5.1 from [34] shows a one dimensional cycle analysis. The efficiency values stated are taken from state-of-the art terrestrial jet engine capabilities.

### 5.2.3 Thermal Control System

Reproduced from [22]:

In order to design a highly efficient lightweight cooling system several options were considered. Among those options, the exceptionally high thermal conductivity of Graphene and Carbon Nanotubes, along with their low mass densities, made these options ideal candidates for the radiator material of the cooling system. Graphene consists of a single plane of sp<sup>2</sup> bonded carbon-carbon atoms and as a result can be considered to be a two-dimensional material. The fact that it is two-dimensional makes Graphene have somewhat unusual properties; two of them are that it has an extremely high thermal conductivity and is incredibly lightweight. Table 5.2 compares Graphene with other materials that have comparatively high thermal conductivity. Using a radiator design similar to the one described by Juhasz in [45], and with a high enough emissivity, a thermal management

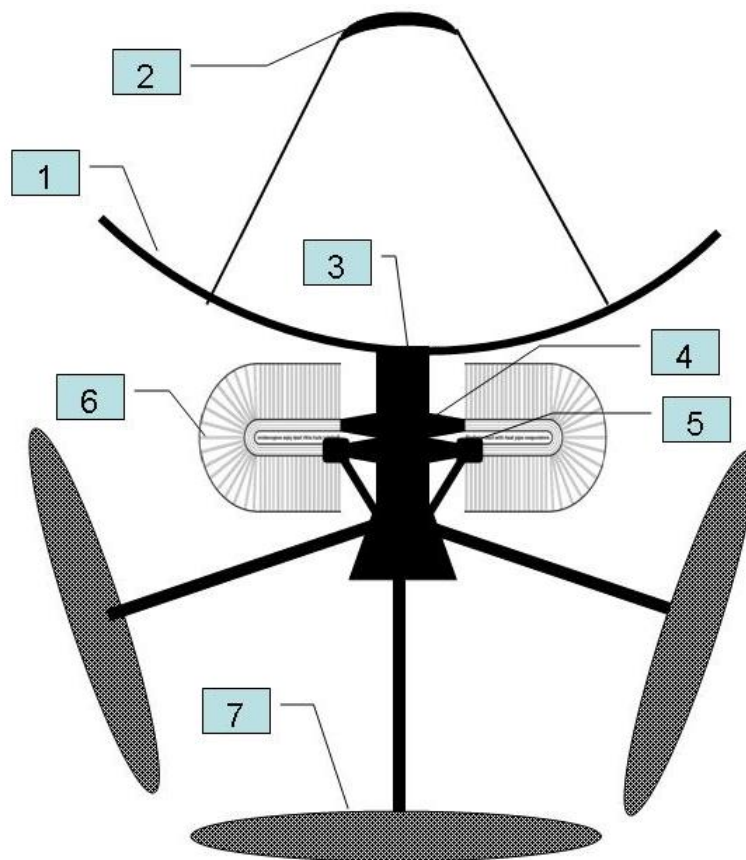


Figure 5.2: Conceptual sketch of the Girasol satellite

Table 5.1: Basic One-Dimensional Cycle Analysis

Station	Parameter Values
Compressor inlet	Station 1
P01	20,000 Pascals
T01	190K
Compressor	station 1-2
Pressure ratio	150
Polytropic efficiency	0.932
Mass flow rate	180 kg/s
Compressor work	1.445 GW
Compressor efficiency	0.846
Start of heat addition	Station 2
P02	3,000,000 Pascals
T02	1642 K
Pre-chiller not used	2-3
P03	3,000,000 Pascals
T03	1642 K
Turbine Inlet	Station 4
Heater pressure loss	10 percent
P04	2,700,000 Pascals
T04	3650 K
Turbine efficiency	99 percent
Turbine exit	Station 4
P05	21,200 Pascals
T05	522K
Turbine work	2.886 GW
Heat removed	Station 6
P06	20,000 Pascals
T06	522 K
High temperature radiator	Station 7
P07	20,000 Pascals
T07	342 K
Heat Rejection work	29 MW
Net work	1.6 GW
Cycle efficiency	0.800

Material	Thermal Conductivity (W/mK)	Areal Density
Graphene Sheet	~3000-5300	6e-7 kg/m <sup>2</sup>
Carbon Nanotubes	~3500	2e-5 kg/m <sup>2</sup>
Pyrolytic Graphite	~1200-1600	~1900 kg/m <sup>3</sup>

Table 5.2: Comparison of thermal conductivity and areal density of Graphene, Carbon Nanotubes and Graphite

system of below 1 kg/m<sup>2</sup> can be easily achieved with the use of Graphene because of its incredibly low mass density. Apart from this, new and developing heat pipe technology similar to one described in [66] hold a strong potential for lightweight and highly efficient heat management systems in space.

Although there is no definite value of thermal conductivity of Graphene that is agreed upon as of yet, the measured values fall between 3000 W/mK to 5300 W/mK for different methods and different conditions [67]. Even as we increase the number of layers, the conductivity decreases approaching that of graphite, but still remains significantly higher than most other materials. Even after considering various effects like losses due to wrinkling of the material, etc., the thermal conductivity of Graphene remains extremely high.

Juhasz proposed a radiator that could achieve 1kg/m<sup>2</sup> in [68]. We conservatively use this value as a specific mass estimate for our thermal control system, noting that with the very low mass density of graphene sheets and the very large scale of the system, it is likely that we could reduce the specific mass considerably lower than this value. The radiator area required was determined from the radiative power equation (shown in equation 5.1). The system mass was then estimated using the specific mass value.

$$P = \epsilon \sigma A T^4 \quad (5.1)$$

$P$  = Power Required to be Radiated from Girasol

$\epsilon$  = Emissivity

$\sigma$  = Stefan-Boltzmann Constant

$T$  = Equilibrium Radiator Operating Temperature

$A$  = Radiator Area Required

A table summarizing the parameters of the Thermal Control System is shown in Table 5.3. Note that the emissivity value is higher than the emissivity of graphene. This is an estimate of the emissivity value of the graphene sheets after the application of coating and paint has been applied. The current design requires radiating a very large amount of power away from the spacecraft (400MW). As a result, a trade study is being performed to evaluate incorporating a recuperator into the brayton cycle turbomachine design, to increase the efficiency of the brayton cycle to see if the power required for radiation can be decreased, in order to decrease the size and mass of the thermal control system.

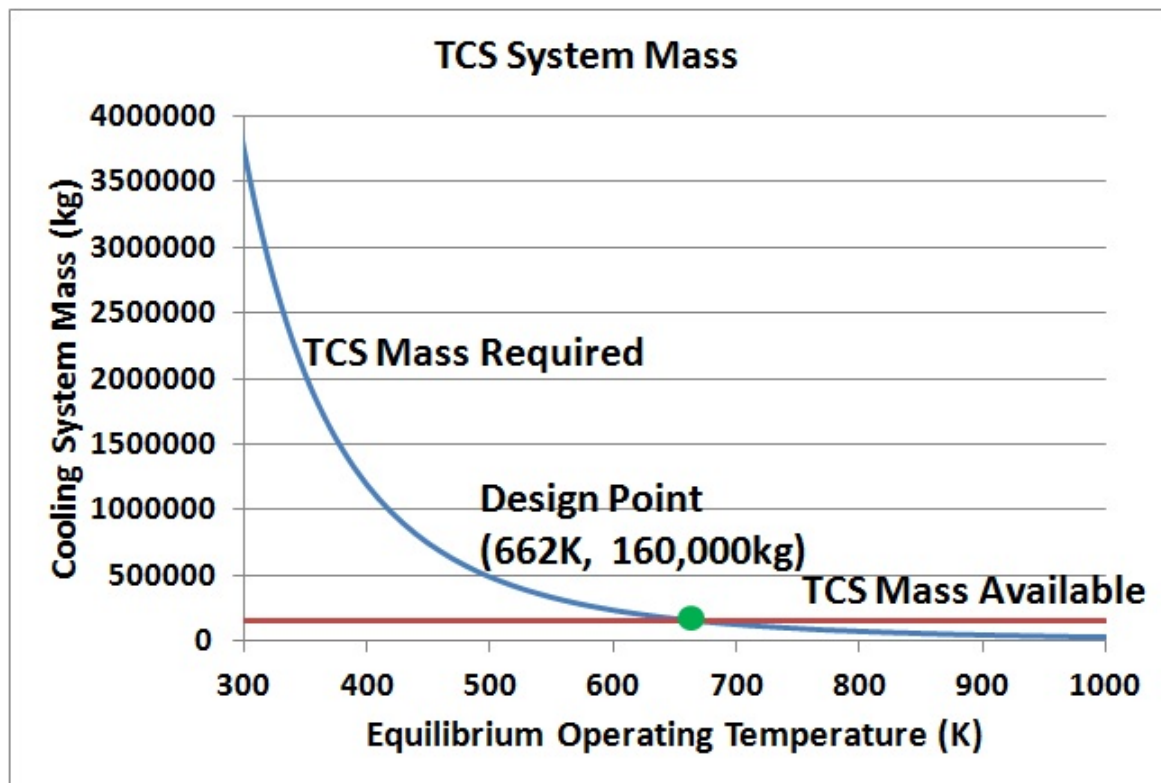


Figure 5.3: Thermal Control System Mass Required for Varying Equilibrium Operating Temperatures

Parameter	Value	Units
Power Required To Be Radiated	400	MW
Operating Temperature	662	K
$\sigma$	$5.67\text{e-}8$	$\text{W}/(\text{m}^2\text{K}^4)$
$\epsilon$	0.23	
Area Required	160,000	$\text{m}^2$
TCS Specific Mass	1	$\text{kg}/\text{m}^2$
TCS System Mass	160,000	kg

Table 5.3: Thermal Control System Parameters

## 5.3 Optical Concentrator Design

The optical concentrator system consists of a large array of individually pointable ultralight thin-film mirrors that collect and concentrate solar energy toward the collector of the girasol for conversion and beaming to ground. The array can be considered as similar conceptually to heliostat arrays on the ground. Some other SSP architectures that have incorporated large arrays of selective elements include the HALO concept [36], the Integrated Symmetrical Concentrator concept [69], and the SPS-ALPHA concept [21]. Those concepts used microwave beaming frequencies and photovoltaic arrays for conversion. The mirasol optical concentrator design was detailed in [22] and is reproduced in the subsections that follow.

### 5.3.1 Configuration

The optical array design consists of a large array of around one thousand ultralight optical reflector elements. The configuration shape has not yet been optimized, but it can be conceptualized as some sort of concave shape with the target of the concentrated solar power being the heater of the brayton cycle heat engine. This design eliminates the need for a large Power Management and Distribution System (PMAD).

When utilizing photovoltaic arrays for conversion, the use of refractive optical elements can be advantageous, as fresnel lens optics can be used to increase the concentration of solar energy multiple times. O'Neill has extensively researched the possible use of stretched fresnel lens refractive concentrator arrays for use in space solar power. O'Neill argues that in the long term, the Stretched Lens Array (SLA) proposed can reach 1 kW/kg for MW level arrays. A 2.5kW Stretched Fresnel Lens array called SCARLET on the Deep Space One Probe demonstrated 45 W/kg specific power [70]. The SLA uses a 140 micron thick fresnel lens array made from a silicone rubber material. Certainly, the use of fresnel lens optics makes sense when using a photovoltaic array for a space-based solar power satellite. For a satellite using solar thermal conversion, such as the one described in this paper, the goal is to maximize the concentration of solar power at minimum mass while incurring the smallest losses. Ultralight reflective optical elements were chosen to achieve very high efficiencies at low mass and as a result were selected as the best conceptual design choice.

### 5.3.2 Material

The material used must be ultrathin and lightweight. The most likely optical materials to meet the design requirements would be some form of polyimide film. A good starting point for selecting a material is to look at materials used for solar sail applications, as solar sail materials are designed to be ultralightweight and highly reflective. Some solar sail demonstration spacecraft have already been deployed. JAXA has successfully deployed the IKAROS spacecraft which uses a polyimide sail. The United States has successfully deployed the Nanosail-D2 spacecraft. This solar sail is 10 square meters, and the spacecraft weighs only 4 kg. It uses an ultralight thin film material called LaRC-CP1 polyimide made by ManTech [71] and developed at NASA Langley, on the order of a few microns in thickness [72]. Solar sail material densities are on the order of 0.01 kg/m<sup>2</sup> [73]. The solar sail material mass was calculated by simply taking the specific mass of solar sail and multiplying by the area required determined from the power required from

the end-to-end efficiency analysis.

### 5.3.3 ADACS Subsystem

An attitude determination and control system (ADACS) is required with actuators and sensors to maintain the necessary sun tracking and pointing requirements. The ADACS includes an actuator and sensor system for each optical element. The mass estimate was determined by allotting 30kg for the ADACS for each element, bringing the total ADACS system mass to 28,800kg.

### 5.3.4 Mirasol Thrusters and Solar Radiation Pressure

The propellant mass requirement becomes the limiting factor on Mirasol specific mass (given that solar sail material can be so light), based on the deltaV requirement from solar radiation pressure. Given the use of ultralight thin film mirrors, the solar radiation pressure becomes a significant mass aspect of the mirasol subsystem. The large area per unit mass value dictates that solar radiation pressure force is substantially high to accelerate the spacecraft out of orbit, which needs to be balanced by some propellant mass. As the propellant mass is increased, the solar radiation pressure force itself drops as the area to mass ratio decreases. In other, more massive architectures using PV arrays, this is still a considerable issue, just not a large mass component, which explains why solar radiation pressure considerations are sometimes neglected in space solar power studies. The Aerospace Corporation SERT report [36] does not ignore it however, and it is considerable for their Halo concept evaluation. Another thing to keep in mind is that the solar radiation pressure force will actually increase as the propellant mass is used up, but the structural and attitude control system mass estimates used in this analysis should be conservative enough to account for this.

The Delta-V required due to the solar radiation pressure force is calculated by equation 5.2.

$$\Delta V = \frac{S * C_r * T}{M/A} \quad (5.2)$$

$S$ =Solar Flux at 1 AU from Sun

$C_r$ =surface reflection index

$T$ =time interval of thrusting

$M/A$  = mass per unit area, specific mass of the mirasol

From this equation it is clear that as the specific mass increases, the less Delta-V will be required.

The deltaV requirements due to solar radiation pressure are plotted in Figure 5.4. Note that the plot starts at 0.01 kg/m<sup>2</sup>, as there is no way to get a lower mass than this because the solar sail material itself has this specific mass value. The plot shows the exponential decrease in Delta-V required with increasing specific mass.

The mirasol array would use krypton thrusters which can achieve a specific impulse of 5300 seconds. Using the rocket equation, the propellant mass required for the mission was calculated over the 17 year spacecraft lifetime. The results are plotted in Figure 5.5.

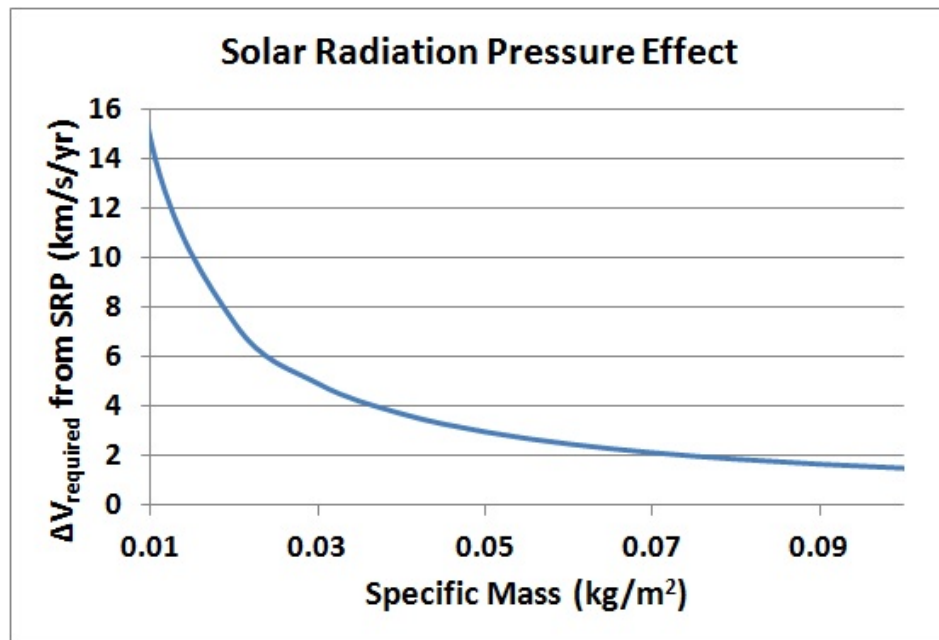


Figure 5.4: Delta-V requirement for different specific mass values for the Mirasol Array

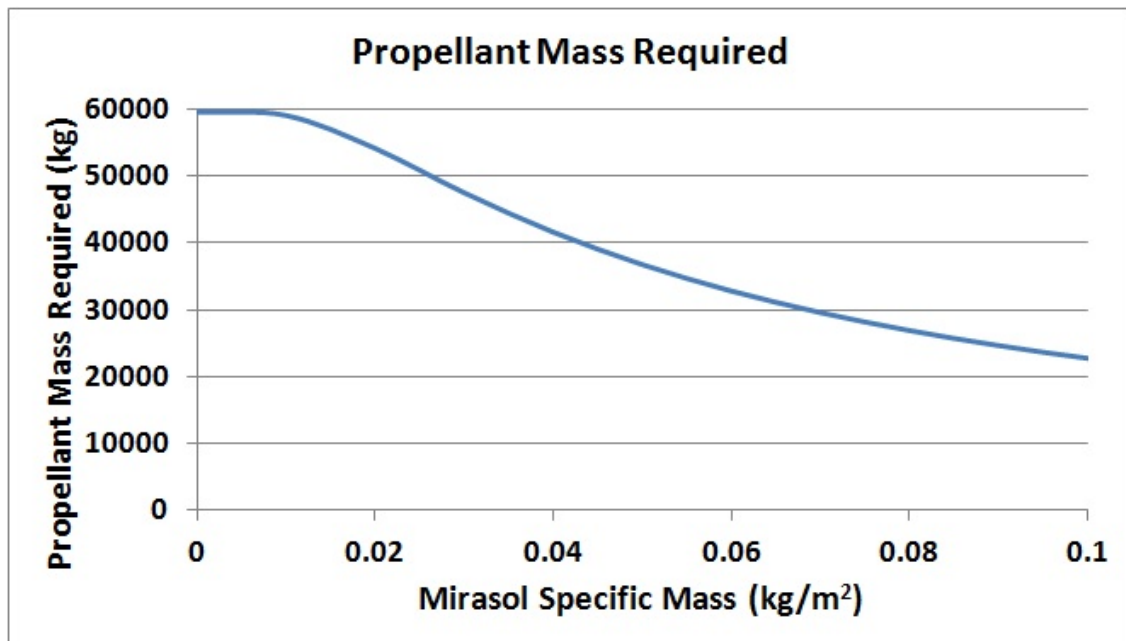


Figure 5.5: Propellant Mass Requirement for Varying Specific Mass Values



Table 5.4: Mirasol Subsystem Mass Summary

Parameter	Mass
Solar Sail Material Mass Required	15356 kg
Mirasol Structural Mass Required	15356 kg
ADACS Mass Required	28800 kg
Mirasol Propellant Mass	32753 kg
Mirasol System Mass	92000 kg

### 5.3.5 Mirasol Subsystem Mass Summary

With the optical material system mass, propellant mass, and ADACS subsystem required mass estimates, the last remaining item is to account for the structural support system for the mirasol concentrator. Roughly 15,000kg has been allotted for the structural support system, an equivalent amount of structural mass as the solar sail material mass was estimated for the support required to maintain tension of the solar sail material for each optical element.

The optimized mirasol system mass was calculated by plotting the mirasol mass required as the constraint, and then plotting the mirasol mass available by the specific power value. Finding the intersection of these two lines gives the minimum specific mass value that meets the mass requirements for each subsystem. As seen in Figure 5.6, the design point is at a specific mass value of  $0.06 \text{ kg/m}^2$ , with a total mirasol system mass coming to about 92,000kg.

## 5.4 Gigawatt Satellite Design Summary

### 5.4.1 End-to-End Efficiency Analysis

A summary of efficiency values is presented in Table 5.5. The mirasol array efficiency is projected at 99%. Currently available commercial materials for space-based reflectors such as Mylar, Teonex, and LaRC-CP1 polyimide can achieve 92% efficiency [73]. However, commercially available heliostat array elements can achieve 99.5% reflectivity [74]. As a result, we believe that with technological improvements in space-based reflector elements, 99% can be achieved. Using hafnium carbide material for the turbomachine components that can withstand the high temperatures needed, an 80% brayton cycle efficiency value was found from the cycle analysis performed in [34].

Perhaps the biggest technical uncertainty of the SPG architecture is in the efficiency of converting the power to millimeter wave frequencies via a millimeter wave generator. Current state of the art technology uses gyrotrons for conversion efficiency over 50%. The 1MW 170GHz gyrotron developed in Japan can achieve 57% efficiency [75]. Gyrotrons bunch electrons together to form millimeter waves. High powered vacuum tubes use a strong magnetic field to create cyclotron motion, where an electron source goes into a strong magnetic field that creates cyclotron motion where some of the electrons are accelerated faster than the other half, creating a bunching effect. Any of the power that is not converted would have to be radiated away as heat. Thus, improving the efficiency is key. A thermoelectric generator system can be used to recuperate some of the lost heat

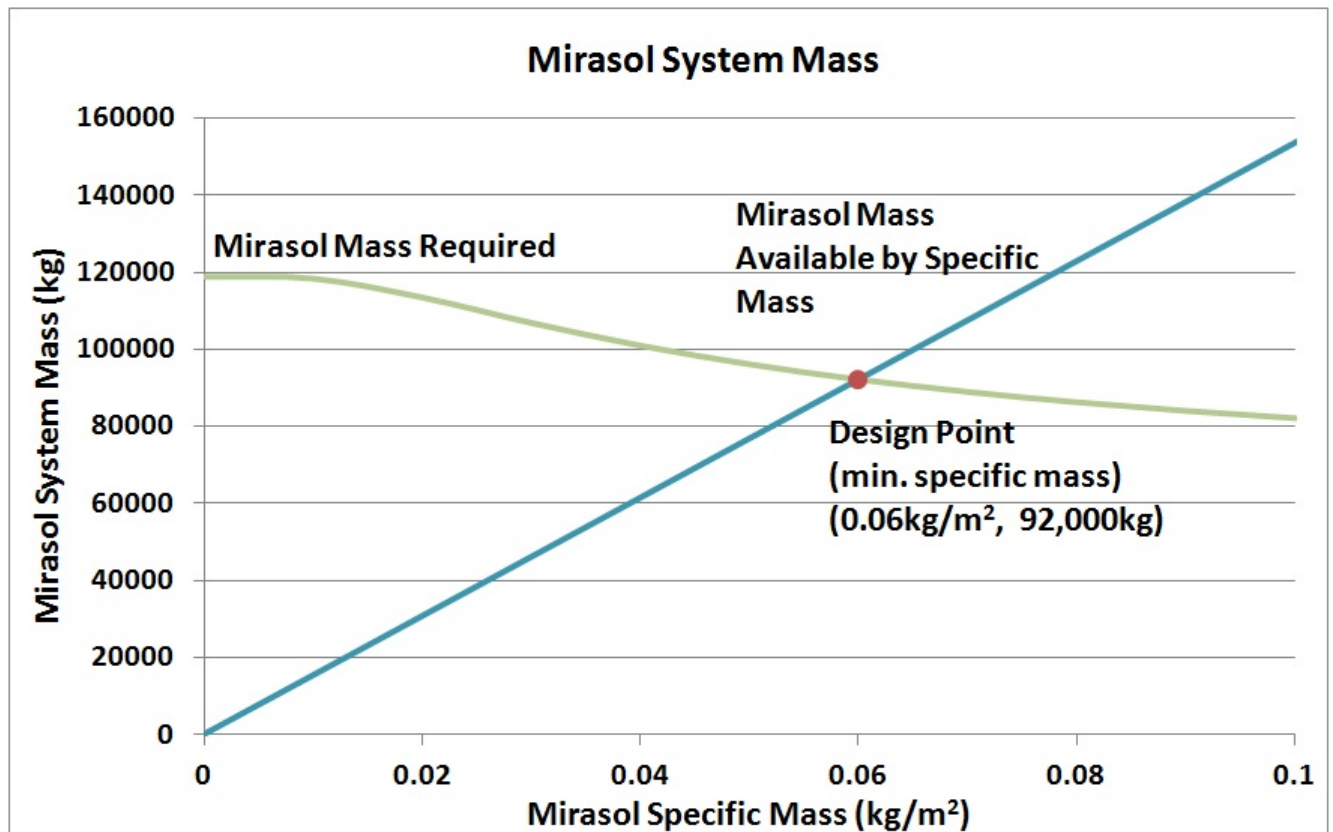


Figure 5.6: Mirasol System Mass for Varying Specific Power Values

to potentially achieve efficiencies near 80% if gyrotrons are used. The biggest size and mass component of a gyrotron system is the high powered magnet and superconducting fluid used to cool it. CPI has developed a 2MW gyrotron [76] for use on an airplane that is designed to be lightweight which uses helium refrigeration rather than liquid helium to cool the magnetic coils. Other options such as solid state devices may be needed in order to achieve the 90% efficiency value used. However, current millimeter wave solid state devices cannot achieve the high power levels needed for space solar power.

A waveguide system for millimeter wave power transmission from the generator to the phased array antennas would be similar to the one detailed in [24], which could achieve 97% efficiency using corrugated waveguide structures similar to the ones described in [77]. Phased array antenna efficiency value cited comes from commonly cited values for antenna efficiency capabilities in the satellite communications industry. Atmospheric transmission windows around 220GHz exist with efficiency values around 90% [78]. The beam capture value of 95% comes from capturing multiple lobes of the diffracted beam pattern, from the analysis performed in Section 4.1.1 of the report.

A 35 GHz rectenna was fabricated with 70% RF to DC conversion efficiency in 1992 with a hybrid rectenna circuit using high power schottky diodes [39]. Currently high power solid state millimeter wave rectennas have not been created, but they could offer 90% efficiency or better. As frequency increases, the diodes must get smaller to avoid impedance issues. This is the reason that efficient high power millimeter wave rectennas have yet to be developed. There does not appear to be any reason, that with increased research and development into manufacturing smaller rectenna components and with recent advances in MEMS manufacturing techniques, that efficiencies cannot be improved

Parameter	Value	Units
Mirasol Power Required	2.09	GW
Mirasol Array Efficiency	0.99	
Brayton Cycle Efficiency	0.80	
Millimeter Wave Generator Efficiency	0.90	
Power After Brayton Conversion	1.49	GW
Waveguide System Efficiency	0.97	
Phased Array Antenna Efficiency	0.90	
Power to Beam	1.30	GW
Atmospheric Transmission Efficiency	0.90	
Beam Capture	0.95	
Rectenna Efficiency (RF to DC)	0.90	
Power to Ground Required	1.00	GWe
End-to End Efficiency	0.48	

Table 5.5: End-to-End Efficiency Breakdown

to reach the 90% values seen for microwave rectenna frequencies.

With these values, the overall end-to-end efficiency of the girasol/mirasol system gigawatt system comes to 0.48% from the power incident on the concentrator system to the electric power delivered to the grid.

### 5.4.2 Mass Summary

A summary of the mass estimates of the given subsystems involved in a girasol-mirasol pair are shown in Table 5.6. In total a 676,700kg system delivering 1GW of power yields a specific power about 1.5kW/kg, a substantial increase in specific power over other proposed photovoltaic architectures that cite values around 0.2kW/kg. This subsystem mass analysis shows that our key mass drivers of the system are the propulsion system and the cooling system. Both of which are heavily reliant on the system reaching high efficiency. Without achieving high efficiency values as outlined in the previous section, the mass required for these systems in order to generate the same amount of power to ground quickly rises.

Element	Mass (kg)	% of Girasol	% of Satellite
Collector	30,000	5.21	4.49
Cooling System	160,000	27.79	23.96
Brayton Cycle	20,000	3.47	2.99
AC generator	50,000	8.68	7.49
Cryogenics	20,000	3.47	2.99
220GHz Amp	17,000	2.95	2.55
Antennae	20,000	3.47	2.99
Propulsion	170,300	29.58	25.50
Misc.	30,930	5.37	4.63
Structure	58,470	10.00	8.62
Total Girasol	584,700	100.00	86.22
Total Mirasol	92,000		13.78
Total Mass	676,700		100.00

Table 5.6: Mass budget for 1 GWe Space Solar Power Satellite

## Chapter 6

# Space Power Grid Architecture Analysis and Economic Calculations

### 6.1 Technical and Economic Assumptions

An architecture analysis code for the Space Power Grid was developed in Fortran. Technical and economic assumptions used are summarized in Table 6.1. Explanations for assumed parameters are enumerated below.

1. B1: The 220GHz window offers up to 90% transmission through a dry atmosphere, compared to 95% below 10GHz, and 92% at 140GHz. Above 10GHz, wet weather operation is poor at low power levels. Continuous megawatt-level beaming through a raincloud remains to be explored. With the tethered aerostat option presented later in this paper, low-loss transmission through the lower atmosphere is enabled using waveguides built into the tethers.
2. B2: Solar power can be converted to DC using high-intensity PV arrays at over 42% efficiency, and from DC to microwave beamed power with roughly 80% efficiency [79]. We assume 40% efficiency with 220GHz conversion. Direct conversion using optical antennae, perhaps made of nanofibers [80] may offer efficiencies well above 40%. Theoretically, 80% conversion is possible. The Intensified Conversion Architecture (InCA) design for the Girasol argues that over 80 percent conversion efficiency can be achieved using primary Brayton cycle conversion.
3. B3: 80% conversion from line frequency to beamed microwaves has been demonstrated. We projected initially that conversion to 220GHz can reach at least this efficiency. However, for single-frequency conversion to 220 GHz, modern solid state amplifiers achieve over 90 percent conversion.
4. B4: A reciprocal conversion efficiency of 90% is deemed possible for the same reason.
5. B5: Atmospheric propagation data at 220GHz [78].
6. B6 and B7: Approximate estimates.
7. B8: Aereal density of 3 to 7 grams per square meter are cited for solar sail craft [73]. Mass including support structures is much smaller than the value that we have assumed.

CHAPTER 6. SPACE POWER GRID ARCHITECTURE ANALYSIS AND  
6.1. TECHNICAL AND ECONOMIC ASSUMPTIONS ECONOMIC CALCULATIONS

Table 6.1: Space Power Grid Baseline Parameter Choices.

Parameter	Value	Basis
Beam Frequency (GHz)	220	B1
Conversion efficiency solar to beam	0.72	B2
Conversion AC to mmwave	0.9	B3
Conversion 220GHz to ground AC	0.9	B4
Efficiency of atmos. pass	0.9	B5
Transmitting Space Antenna kg/m <sup>2</sup>	0.05	B6
Receiving Space Antenna kg/m <sup>2</sup>	0.05	B7
Ultralight Reflector Satellite kg/m <sup>2</sup>	0.01	B8
Miscellaneous mass added	5%	B9
Collector kg/m <sup>2</sup> of converter sat	0.05	B10
Converter kg/MWe at 300 Suns	500	B11
Efficiency of reception at Satellite	0.961	B12
Efficiency of capture at ground	0.961	B13
Efficiency of ground antenna	0.9	B14
Diameter of Phase 1 sat receiver, m	50	B15
Orbit height of Phase 1 sat, km	2000	B16
Half-angle of azimuth visibility, deg.	45.	B17
Distance between satellites (km)	2400.	B18
Power transmitted (design, MW)	60.	B19
Phase 2 collector diameter, m	300.	B20
Cooling system kg/MW of heat	400.	B21
Launch cost to LEO, Phase 1 \$ per kg	2500	B22
Launch cost to LEO, Phase 2-3\$ per kg	1300	B22
Isp for orbit transfer, sec.	5300.	B23
Operations cost per sat \$M	5.	B24
Satellite other systems mass:	1000kg	B25
Ground facilities development \$M	1000.	B26
\$M cost per ground facility cost	25.	B27
\$ per kwh to produce power, ground	0.04	B28
Sales price, \$ per KWh, Phase 1	0.17	B29
Number of stations participating	250.	B30
MW average per plant	60.	B31
Assumed Discount Rate, percent	6%	B32
Desired Return on Investment, Ph1 %	6%	B33
Desired Return on Investment, Ph2 %	6%	B34
Loan percentage, Phase 1	30%	B35
Loan percentage, Phases 2 and 3	30%	B36
Sales price, \$ per KWh, Phase 3 SSP	0.11-0.15	B37

8. B9: A 5% allowance for other systems is conservative but we have not detailed the subsystems.

9. B10: Reflector may be similar to B8, but some thermal control is needed in view of the intensified sunlight, and lower Phase 2 orbits demand stronger structures.

10. B11: Converter mass per unit power is a critical limiting technology. We assume this value of 0.5 Kg/MWe at large power levels with 300-sun intensified sunlight. It is feasible with direct conversion or mechanical-electric conversion.
11. B12: The Phase 1 SPG satellite is conceptualized as transmitting and receiving antennae connected through waveguides, with minimal internal dissipation. This drives thermal management system mass. For a narrow-band tuned antenna and waveguides, 1% loss may be conservative. The waveguides now specified, which are capable of handling a broader range of millimeter waves, achieve considerably better than that transmission at 220 GHz.
12. B13: With 220GHz, the antennae is sized for 96.1% capture with an Airy constant of 10.49 in the equation for diffraction-limited antenna size, rather than the 84 percent achieved with a constant of 2.44.
13. B14: Ground antenna efficiency is taken as 0.9 based on claims of people in the microwave beaming community.
14. B15: The effective diameter of the receiving antenna on the Phase 1 spacecraft is taken to be 50m.
15. B16: Orbit height of 1900+ miles enables a sun-synchronous orbit where each satellite stays in view for a few minutes each time.
16. B17: Each ground station is assumed to have a clear view of the sky down to 45 degrees from the zenith. This is conservative, but atmospheric propagation loss data are available for 45-degree transmission. [78]
17. B18: A design distance of 2400km is chosen for intersatellite beaming, to size the space antennae. When used for longer distance beaming, this implies either a loss at the receiver or a need for larger receivers.
18. B19: Because revenue comes from transacted power, there is a lower limit on the power transacted per satellite, for economic viability. This limit may be down near 10MW. The 60MW level is chosen because the intensities of beams at the ground and at the spacecraft are still kept moderate.
19. B20: Collector diameter is set to 300m arbitrarily.
20. B21: Cooling system mass: The assumed level is roughly half of that on an existing spacecraft. Note that with the Phase 1 satellites and Girasols, total system mass is used directly from the papers on their conceptual design, in the relevant architecture cases. Refer to those papers for details.
21. B22: Launch cost to LEO is assumed at reasonable minimum achievable value for the near term in Phase 1, and at a value projected by SSP proponents for the long-term, to be consistent with other SSP architecture projections.
22. B23: Transfer from LEO to final orbits, and orbit corrections, are assumed to use Krypton thrusters and the required delta-v is doubled from the Hohman transfer level to account for the continuous low-thrust mode.

23. B24: \$5M per year/satellite from NASA-Air Force Cost Model, for 36 sats. Cost decreases as constellation grows.
24. B25: An allowance of 1000Kg provides for miscellaneous sensors and systems on each Phase 1 craft.
25. B26: \$1B development cost assumed, for the technology and procedures to exchange beamed power with satellites. The number of ground stations is assumed to be twice the number of Phase 1 and Phase 2 satellites. As Phase 3 starts, the older Phase 1 stations have to be upgraded to receive the 1GWe level of beaming from the Phase 2 and Phase 3 satellites.
26. B27: In addition, a \$25M cost is assigned to each ground facility to install equipment to interact with SPG.
27. B28: Typical US utility power production cost \$0.04 per KWH.
28. B29: Assume that Phase 1 SPG power will be sold at 17 cents per KWH. Customers at solar plants will find this reasonable because it saves the immense costs of installing auxiliary generation equipment.
29. B30 and 31: The SPG part of the ground facilities are attuned to the parameters of the satellites.
30. B32: 6% discount rate on financing needed for the SPG, given low interest rates prevailing today, and given that the massive investment needed for Phase 2 SPG can only come through international collaboration and central banks.
31. B33 and 34: In Phase 1, governments will hold expected Return on Investment to 6%, for the same reason as given above. In Phase 2, nations have the choice of getting larger ROI by deploying satellites slower, or investing heavily and ramping up the SSP rapidly.
32. B35 and 36: A loan percentage of 30% is assumed.
33. B37: Phase 3 sales price of power to break even by Year 50 at the given ramp-up rate, varies for the different cases considered.

## 6.2 Analysis Results

Analyzing the results of the architecture code reveals that traditional architectures fall about two orders of magnitude short of achieving viability given the technical and economic assumptions outlined in the previous section. The results of the architecture analysis were first described in [23], where the 'Ngorongoro' viability parameter  $k$  was first introduced. At the following IEEE Aerospace conference in 2012, the architecture analysis was refined in [32] to include improvements in the architecture design, with the primary change being the incorporation of brayton cycle solar thermal conversion.



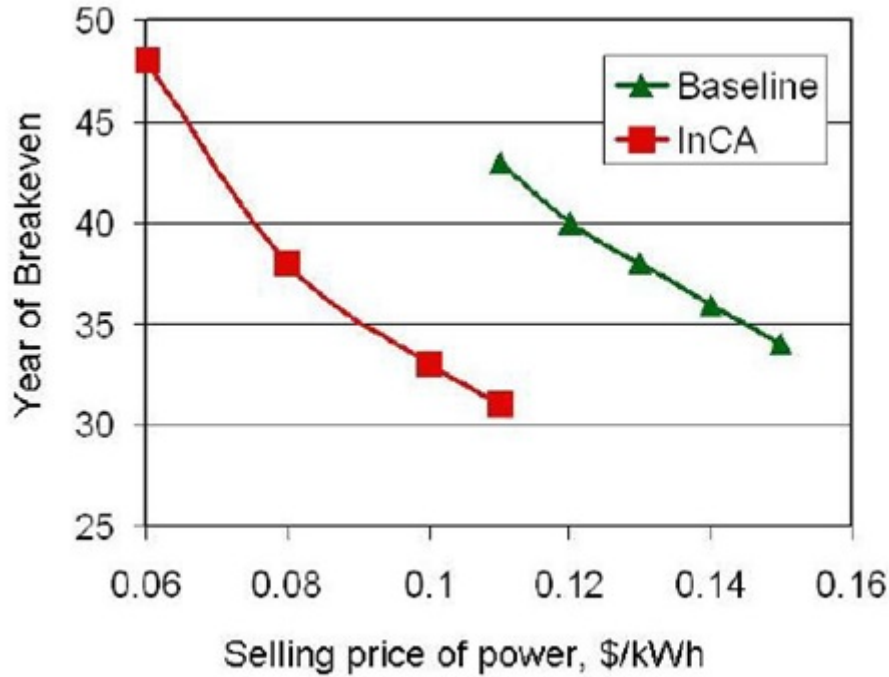


Figure 6.1: Plot showing System Breakeven Year for Difference Selling Price of Power

### Sensitivity Analysis

The energy market and economic conditions around the world over the next 40 or so years is very difficult to predict. As a result, sensitivities were performed to some of the economic parameters of the architecture. Figures 6.1 and 6.2 show sensitivity results for changes in the selling price commanded of space solar power as dictated by market conditions. In Figure 6.1, the baseline SPG architecture is seen to breakeven only if space-based power can be sold at 11-15 cents per kilowatt-hour. This plot shows the large improvement when brayton cycle conversion (the InCA architecture) is introduced. As the selling price decreases, an exponential increase in the years needed to breakeven is seen. Figure 6.2 shows the sensitivity of the selling price on the viability parameter introduced earlier. At  $k \sim 1$  is where the architecture is reasonably assumed to be economically viable. As is shown, the InCA architecture can achieve a value close to viability at much lower selling prices.

### Net Present Value

The net present value plots allow us to see the effect of different parameters on the investment required over time as well as the amount of time needed to breakeven. Figure 6.3 shows a net present value chart for the Phase 1 power exchange only. This chart shows that the investment required for this phase is very reasonable compared to several other large space based programs and orders of magnitude smaller than incorporating the large-scale investment needed for Phase 2. By demonstrating several of the power beaming technologies needed for a large-scale architecture, the technology risk of launching large solar power satellites is reduced while the time allows research and development to mature conversion technologies. In Figure 6.4 the net present value chart for the full architecture

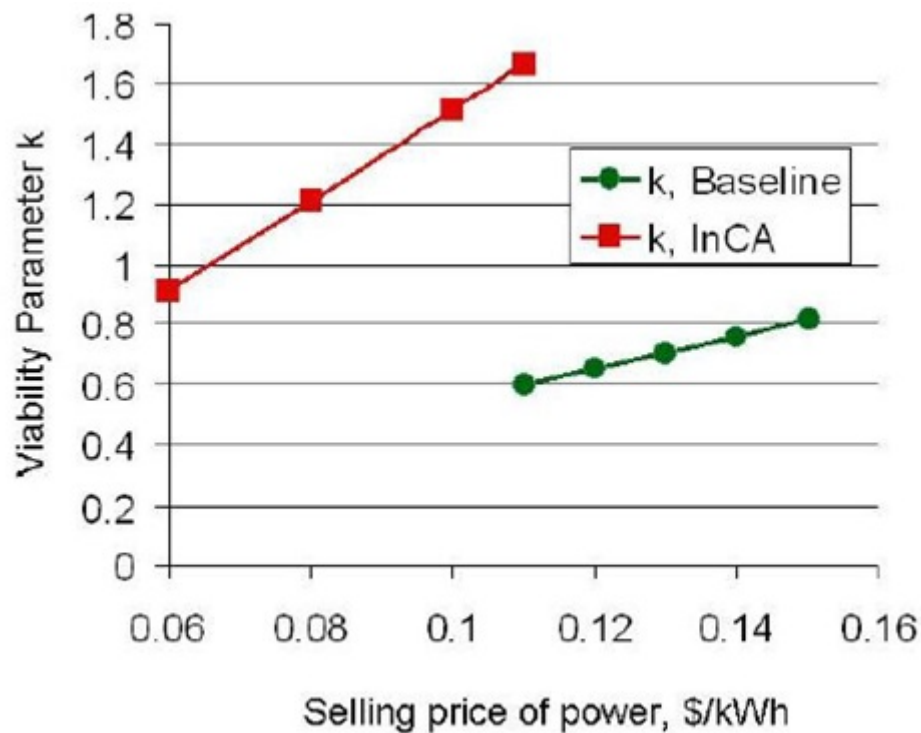


Figure 6.2: Plot of Viability Parameter Value at Different Selling Price of Power

is shown. This plot shows the large improvement in the breakeven time and investment required over the baseline architecture and the importance of the selling price of space based power. It also shows that the investment required for the initial phase 1 relay is miniscule (on the order of billions) compared to the investment required for terrawatt level power production (on the order of trillions). It is generally assumed that space based power can command about 10 cents per kilowatt-hour. In the United States, power prices are generally around 2-4 cents per kilowatt-hour. However, during peak usage these numbers can increase to 10-20 cents per kilowatt-hour or considerably higher. These prices assume a well-established infrastructure for delivering power. This is not the case in many areas of the world, where a large percentage of the population does not enjoy power at these prices. The anywhere, anytime capability of a space power grid architecture delivering power over the world can deliver power to areas of high demand and command considerably higher prices. Thus, the assumption that space power can command prices around 10 cents per kilowatt-hour seems to be a reasonable one. From this plot, it is seen that the SPG architecture can achieve 4-terrawatt level power production and reach breakeven in roughly 30-45 years from project start depending on the selling price of space power.

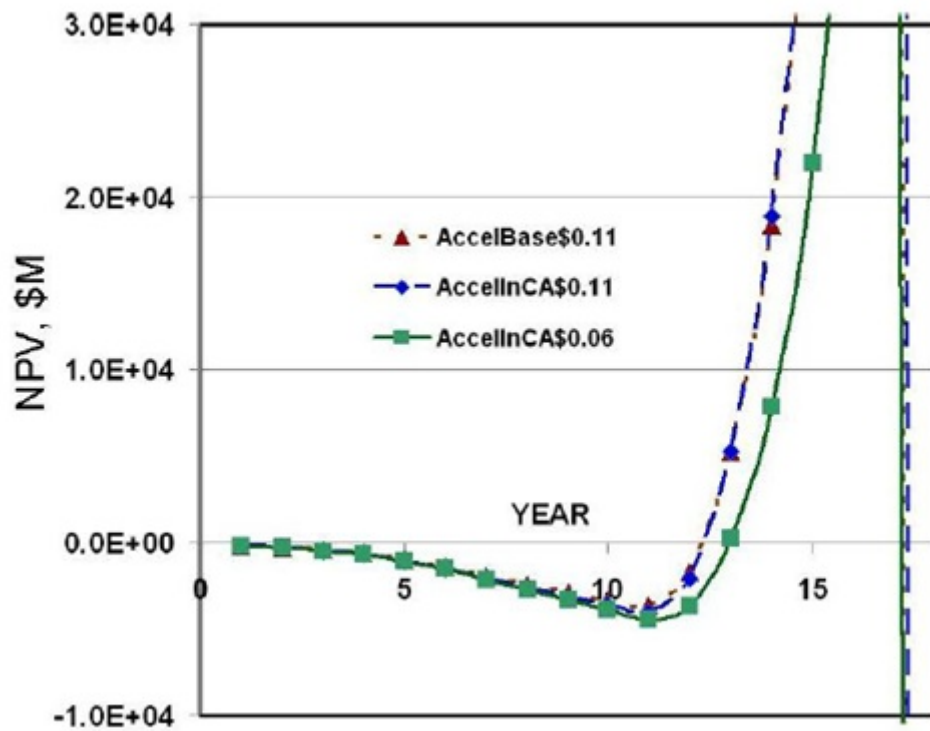


Figure 6.3: Net Present Value for Phase 1

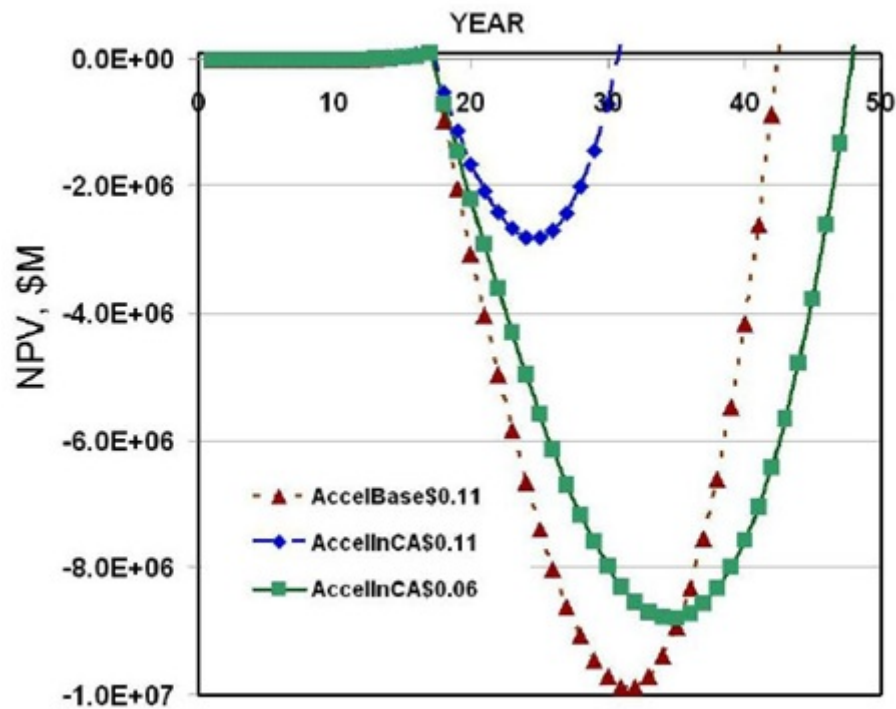


Figure 6.4: Net Present Value for Full System Architecture



# Chapter 7

## Summary and Conclusions

The Space Power Grid architecture proposes innovative solutions to the space-based solar power problem. This report recognizes the significant technical risks associated with developing a space-based solar power architecture. Particularly, the risks associated with the ability to efficiently convert to and from millimeter wave frequencies, as these devices currently do not reach the efficiency values needed. The added technical risk of millimeter-wave based architectures is seen as a necessary trade in reducing the system size of traditional SSP architectures. Our architecture does not determine a specific project start date, rather a plan that outlines benchmarks from project start is used. Predicting the economic and technological environment even 5-10 years from now can be very difficult, and this approach allows some flexibility. This flexibility allows for technology to develop to reach the Technology Readiness Levels needed to improve viability and decrease the risk associated with this or any other space solar power architecture. In this sense, this report tries to outline what is needed to move towards large-scale space solar power, rather than to argue that this architecture can be started today. Specific conclusions from this report are itemized below:

1. Innovative solutions are necessary to bring about the significant improvements needed in viability over traditional GEO-based, microwave beaming architectures that utilize photovoltaic conversion of solar energy.
2. A multinational demonstration of space power beaming is seen as an important first step in meeting several technical and public policy objectives necessary in jumpstarting a large-scale space solar power project.
3. Due to the magnitude of the infrastructure investment needed for large-scale SSP, an evolutionary approach is necessary in order to gain interest from funding entities. A first phase of the featuring a constellation of around 100 L/MEO 4000kg class relay satellites that would establish a power exchange through space can provide a key step in an evolutionary architecture
4. Coming down from geosynchronous orbits to dynamic orbits in L/MEO around 2000km is seen as an important architecture change in reducing system size.
5. The use of brayton cycle solar thermal conversion of concentrated solar energy is seen as having the potential to greatly improve system viability by offering significant improvements in specific power ( $\sim 1.5\text{kWe/kg}$ ) over photovoltaic conversion systems ( $\sim 0.2\text{kWe/kg}$ ).

6. The millimeter wave frequency regime offers a good compromise between the benefits of microwave and laser based SSP systems. Efficient atmospheric transmission windows around 220GHz are shown as a promising high frequency selection for a SSP system
7. Development of efficient millimeter wave conversion devices is seen as the greatest potential risk to the viability of the SPG architecture.
8. Using the technical and economic assumptions given in Chapter 6, the SPG architecture can be reasonably assured to be viable and can reach breakeven within 40 years from project start while achieving terrawatt level power production ( $\sim 4\text{TW}$ ).

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